DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OPTIMIZING ENERGY EFFICIENCY AT COMBI BOILERS WITH WIRELESS SENSOR NETWORKS

by

Erçin TEOMAN

February, 2024

İZMİR

OPTIMIZING ENERGY EFFICIENCY AT COMBI BOILERS WITH WIRELESS SENSOR NETWORKS

A Thesis Submitted to the
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In Partial Fulfillment of the Requirements for Master of Science in
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by

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THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **“OPTIMIZING ENERGY EFFICIENCY AT COMBI BOILERS WITH WIRELESS SENSOR NETWORKS”** completed by **ERÇİN TEOMAN** under supervision of **ASST.PROF.DR. LÜTFİYE ÖZLEM AKKAN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Asst.Prof.Dr. Lütfiye Özlem AKKAN

Supervisor

Asst.Prof.Dr. Dilşad ENGİN	Prof.Dr. Zeki KIRAL
Jury Member	Jury Member

Prof. Dr. Okan FISTIKOĞLU
Director
Graduate School of Natural and Applied Sciences

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OPTIMIZING ENERGY EFFICIENCY AT COMBI BOILERS WITH WIRELESS SENSOR NETWORKS

ABSTRACT

The aim of this thesis is to contribute to the global effort to mitigate the impacts of the energy crisis, with a particular emphasis on sustainable gas consumption in Türkiye, where approximately sixty percent of the population is dependent on natural gas. The primary objective is to design an optimization algorithm that utilizes domestic sensor networks specifically tailored to enhance the efficiency of gas-fired combi boilers used in residential heating, rooted in the principles of sustainability. The objective of the proposed algorithm is to reduce energy consumption and promote responsible usage of natural gas in households, while also moving towards a more environmentally friendly direction for residential heating systems. This thesis will include the design and implementation of an intelligent system with MQTT communication capabilities to enable remote control and monitoring of the gas-fired combi boiler and the connected radiators. This system utilizes IoT technology to optimize gas-based heating systems, providing real-time insights and dynamic adjustments based on household needs and environmental conditions. It aligns with broader sustainability goals and promotes responsible usage.

Keywords: Gas-fired combi boilers, optimization of residential heating, natural gas use in Türkiye, energy-efficient practices, sustainability in heating systems.

KABLOSUZ SENSÖR AĞLARI İLE KOMBİLERDE ENERJİ VERİMLİLİĞİ OPTİMİZASYONU

ÖZ

Bu tezin amacı, nüfusun yaklaşık yüzde altmışının doğalgaza bağımlı olduğu Türkiye'de sürdürülebilir gaz tüketimine özel bir vurgu yaparak, enerji krizinin etkilerini azaltmaya yönelik küresel çabalara katkıda bulunmaktır. Birincil amaç, konut ısıtmasında kullanılan gaz yakıtlı kombilerin verimliliğini artırmak için özel olarak uyarlanmış evsel sensör ağlarını kullanan ve sürdürülebilirlik ilkelerine dayanan bir optimizasyon algoritması tasarlamaktır. Önerilen algoritmanın amacı, enerji tüketimini azaltmak ve evlerde doğal gazın sorumlu kullanımını teşvik etmek, aynı zamanda konut ısıtma sistemleri için daha çevre dostu bir yöne doğru ilerlemektir. Bu tez, gaz yakıtlı kombinin ve bağlı radyatörlerin uzaktan kontrolünü ve izlenmesini sağlamak için MQTT iletişim özelliklerine sahip akıllı bir sistemin tasarımını ve uygulamasını içerecektir. Bu sistem, gaz tabanlı ısıtma sistemlerini optimize etmek için IoT teknolojisini kullanmakta, hane halkı ihtiyaçlarına ve çevresel koşullara göre gerçek zamanlı bilgiler ve dinamik ayarlamalar sağlamaktadır. Daha geniş sürdürülebilirlik hedefleriyle uyumludur ve sorumlu kullanımı teşvik eder.

Anahtar kelimeler: Gaz yakıtlı kombiler, konut ısıtmasının optimizasyonu, Türkiye'de doğal gaz kullanımı, enerji verimliliği uygulamaları, ısıtma sistemlerinde sürdürülebilirlik.

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LIST OF SYMBOLS

°C	: Celsius
t	: Time
ρ	: Density
c	: Specific heat
T	: Temperature
kW/h	: Kilowatts per Hour
k	: Thermal conductivity
∇T	: Temperature gradient
$\boldsymbol{q}$	: Conductive heat flux
$\partial/\partial t$	: Time derivative
$\oint$	: Surface integral
∇	: Gradient operator
$\langle ... \rangle$	: Contains.

ABBREVIATIONS

MQTT : Message Queuing Telemetry Transport

EC : European Commission

Erp : Energy Related Products

IoT : Internet of Things

AMQP : Advanced Message Queuing Protocol

CoAP : Constrained Application Protocol

HTTP : Hypertext Transfer Protocol

REST : Representational State Transfer

UDP : User Datagram Protocol

QoS : Quality of Service

IR : Infrared

EMI : Electromagnetic Interference

SoC : System on a Chip

DC : Direct Current

AC : Alternative Current

DHW : Domestic Hot Water

DCW : Domestic Cold Water

CH : Central Heating

CO_2 : Carbon Dioxide

BR : Bluetooth Basic Rate

EDR : Enhanced Data Rate

BLE : Bluetooth Low Energy

NWK : The Zigbee Network Layer

APS : Application Support Sublayer

ZDO : ZigBee Device Objects Sublayer

PCB : Printed Circuit Board

AT : Apparent Temperature

T : Temperature

RH : Relative Humidity

HMI : Human Machine Interface

CHAPTER ONE
INTRODUCTION

1.1 Study Area

In the context of today, there are numerous applications and initiatives in the realm of smart homes. However, it is essential to understand the origins of this concept. These applications emerged from the foundational knowledge and expertise derived from the fundamental sciences. When these applications first emerged, they were a product of the pathways paved by accumulated knowledge. The concept of smart homes originated in the 1950s, with the Push Button Mansion serving as an early example. Since its inception, this concept has undergone several changes, with various features being integrated over time. The Push Button Mansion project was an innovative application, introducing several unique options such as windows and doors that automatically close in the rain, light bulbs that activate with a bell press, and an algorithm for fire and theft alarms (Railton, 1950).

In recent years, studies have been conducted on energy and waste management, particularly around system security (Han et al., 2014; Kumar, 2014). The smart home system controls all smart devices and sensors used in smart home applications. The devices within the smart home system should communicate with each other, which is possible with the MQTT Protocol supported by Wi-Fi and the main controller when necessary. Research shows that the number of devices interacting with each other has increased significantly over the years. In 2003, the number was around six hundred million, but today it has reached fifteen billion. It is estimated that this number will further increase to about fifty-five billion by 2020 (Ashton, 1999).

The Internet of Things (IoT) is a network system that enables smart devices to communicate with each other using various communication protocols. It has become increasingly prevalent with the development of technology. IoT systems operate under many topics. These studies classify the security of IoT systems, the performance of communication protocols and applications in various fields. Lee et al. (2013) conducted research on IoT security. The literature review compares the performance of communication protocols used in IoT systems. Smart home systems use various protocols, and Wi-Fi-based setups tend to have installation costs higher than expected. It is important to note their global suitability for data reception and usage. They offer high-speed data transfer and perfect accuracy, making them the preferred choice for many. Wi-Fi-based systems are popular due to their adaptability to diverse environments and widespread compatibility. While other systems may excel in specific aspects, Wi-Fi is established as a reliable and efficient solution for smart home applications due to its combination of low installation costs, speed, and global usability (Hasan et al., 2018).

The second chapter examines consumption and trends in the global and Turkish natural gas sectors. It also investigates the energy efficiency and sustainability of target combi boilers. The third chapter explores a method for finding solutions to the issues studied in the second chapter, including comparisons with similar sectors and all inputs of thesis study. The experimental phase began in the fourth chapter, utilizing algorithm-supported software to work on the solution. The last section details the tests performed and the results obtained.

1.2 Purpose & Scope

Statistical studies show a steady increase in interest for smart home solutions. However, in Türkiye, due to high electricity tariffs, natural gas remains the most cost-effective option. Therefore, it is recommended that people consider smart home concepts that incorporate gas-operated boilers. The forecast for the 'Smart Homes by Segment' indicator is intriguing (Dimitrokali et al., 2015). The increase observed across all segments from 2020 to 2028 is significant and consistent, indicating a strong and sustained trend. It is noteworthy that the Smart Home segment is projected to reach approximately nine million users by 2028, highlighting the widespread adoption and growing popularity of smart home technologies. This reflects a broader societal shift towards embracing advanced home automation. The analysis in Figure 1.1 highlights the importance of our chosen field of study in Türkiye, indicating a promising future for the integration of smart home solutions across various segments.

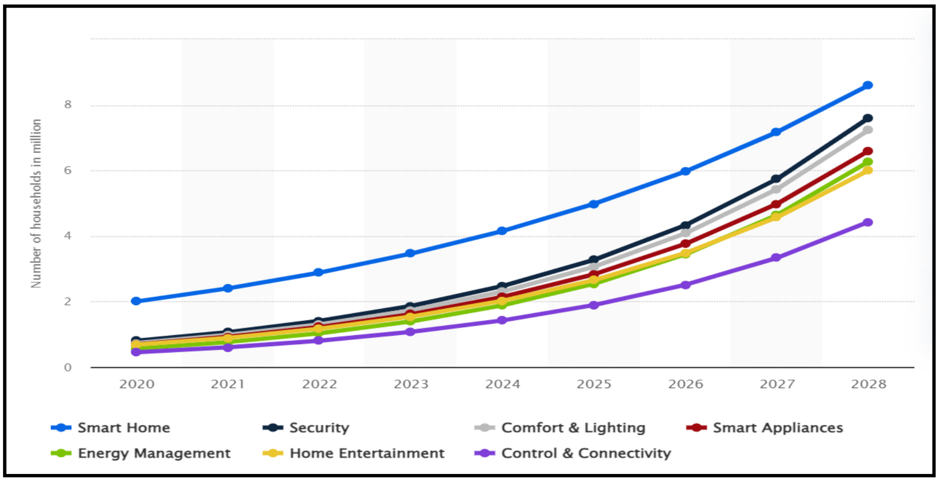


Figure 1.1 Number of households for segment in Türkiye between 2020 and 2028 (Statista, 2023)

Regrettably, numerous combi boilers in Türkiye are still operating without remote controls, but there is a growing interest in smart home systems. Users require information on the efficiency they can achieve. It is crucial for a product and solution to emerge at a cost not exceeding 10% of the investment cost of the necessary plumbing and gas-operated boiler for a house. When considering the geography of Türkiye, the monthly household gas consumption, as shown in Table 1.1, is approximately 145 cubic meters. The aim is to enhance the efficiency of wireless sensor networks. The target is to reduce the average to 140 cubic meters initially and then to 135 cubic meters in the future. Any changes in global temperature values will also be assessed (Gazbir, 2022).

Table 1.1 Gas consumption per household in Türkiye (cubic meter) (Gazbir, 2022)

2017-2018	89	135	183	159	135	140	.
2018-2019	75	159	203	177	156	154	10%
2019-2020	48	127	189	174	137	135	-12%
2020-2021	69	137	161	159	166	138	3%
2021-2022	71	152	183	195	178	156	13%
Months	October	December	January	February	March	Winter Average	Difference

Computer simulations have been used to investigate the potential energy savings associated with advanced smart home thermostat technologies. For example, Lu et al. (2012) conducted simulations to measure the average energy-saving ratio of smart thermostats equipped with occupancy sensing in five U.S. cities, revealing savings of over 25%. An investigation was conducted using a co-simulation framework that combined various tools to calculate the energy savings of HVAC systems in residential buildings that use occupancy-centric HVAC controls. The efficacy ranged approximately 22.5%, depending on the local climate (Wang et al., 2020).

In a separate nationwide study, a comprehensive simulation was carried out to measure the energy-saving potential of smart thermostats in forty representative cities across the United States. The study revealed that almost 75% of the cities demonstrated an efficiency of less than 14% when using a four-degree Celsius occupied-standby temperature setback. Furthermore, depending on the local climate, an eight-degree Celsius setback temperature could result in an additional efficiency gain of approximately 7.5%, compared to the four-degree Celsius setback strategy (Pang et al., 2018).

Although simulation-based studies have benefits, such as cost-effectiveness, versatility in assessing multiple locations, and prolonged analysis compared to field testing, their findings may be unreliable due to inherent limitations. It is important to note that the effectiveness of energy savings resulting from temperature setbacks depends significantly on household profiles, which are influenced by factors such as the number, age, and employment status of household members. Any changes to occupancy assumptions can significantly affect potential energy savings. Additionally, many simulation-based studies assume flawless sensor performance when calculating HVAC energy consumption, ignoring the inevitability of errors in real-world operations. This deviation from reality can introduce biases when evaluating energy-saving outcomes.

CHAPTER TWO

STUDIES

2.1 Consumption of Natural Gas and Using Combi Boilers Worldwide

The decarbonization of the heating sector presents a significant challenge due to a complex interplay of structural and human factors, including entrenched infrastructures and resistant social practices (Hansen, 2018, 2016). In the UK, residential heating, which includes space heating and hot water (15%), contributes significantly to carbon emissions, accounting for about 20% of the country's overall emissions (Palmer and Cooper, 2013; BEIS, 2016; ETI, 2015). According to Abu-Bakar et al. (2013) and NIC (2018), the UK's spending on heat has increased from £5 billion in 1970 to £134 billion in 2011, and the estimated cost of decarbonization is £450 billion. The financial dimension of the heating sector in the UK is significant. However, the sector is plagued by inefficiencies and wasteful practices. According to a survey, 98% of English homes use gas boilers with basic controls, and a considerable number of UK homes lack essential heating controls altogether (Munton et al., 2014; Department of Energy and Climate Change, 2012). Gas boilers remain the dominant choice, with sales reaching a record high of 1.67 million units in 2019, providing gas central heating to twenty-two million homes (Installer Magazine, 2020).

Although 60% of gas-connected homes in the UK have higher efficiency condensing boilers, their potential remains unrealized without adequate controls. In addition, heating density plots reveal a prevalent habit of leaving heating systems on continuously. Low-carbon heating is still uncommon in the UK, as evidenced by BEIS (2018) data indicating that 85% rely on gas central heating, with 90% of homes preferring gas when given a choice (Climate Change Committee 2016; DECC, 2013).

The data obtained from a Living Laboratory, which involved one hundred homes across the United Kingdom (Global Environmental Change, 2020), coupled with supplementary surveys and repeated household interviews, reveals significant variability in temperature preferences within households. Preferences range from simple dichotomies such as heating on or off to more intricate profiles like 'Hot & Cold

Fluctuates' or 'On-demand Sizzlers.' The findings indicate an increasing need for intelligent heating control solutions as consumer behaviour and thermal comfort preferences evolve together. The use of advanced controls can improve consumer understanding of different heating experiences over time. Households that use smart controls can refine their heating preferences by distinguishing between air temperature and radiant heat or expressing preferences for when heating activates in specific rooms. Three key conclusions can be drawn from these observations, which have policy implications for engineers, researchers, businesses in the energy sector, and local and national planners. It is important to invest in systems that cater to individual preferences while also aligning with broader objectives of improvement and decarbonization. Although this research focuses on Türkiye, the interest in gas-fired heating systems remains consistent across countries. Let us expand our target area beyond Türkiye. Figure 2.1 shows that sales of domestic combi boilers are substantial and growing in Russia. This trend is observed in countries where natural gas is the primary energy source, whether imported or exported.

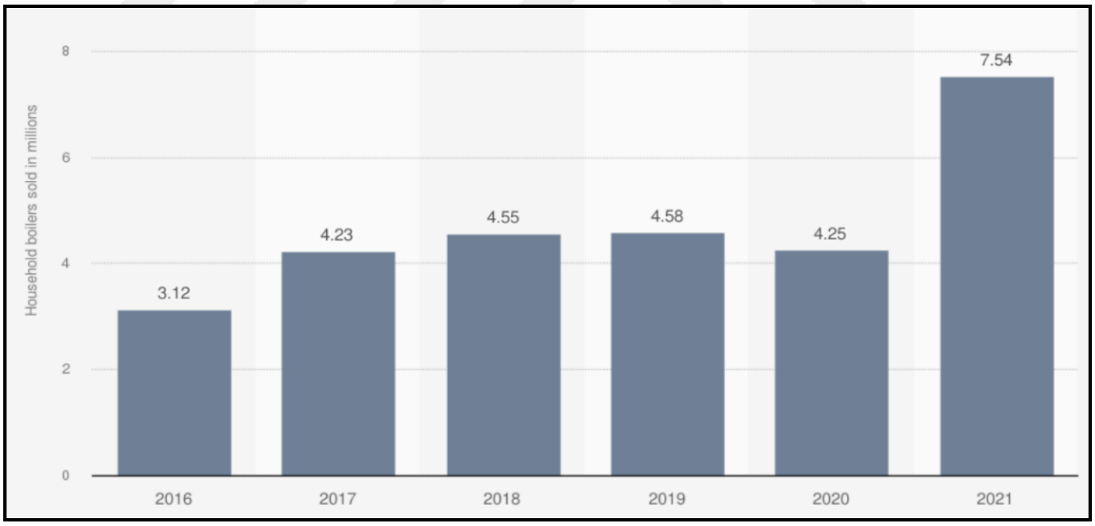


Figure 2.1 Number of boilers sold in Russia between 2016 and 2021 (in millions) (RBC.ru, 2022)

Gas-fired boilers remain the most reliable heating source in Germany, despite global war conditions. Although interest in heat pumps is increasing, their design inherently leads to significantly lower capacities in kilowatts (kW), particularly in wintry weather conditions.

However, it is not advisable to invest in devices with capacities well above actual needs, even if some decreases are tolerated. Even in Germany, which is considered the industrial powerhouse of Europe, there is still considerable demand for gas-fired boilers, as shown in Figure 2.2. The demand for gas-fired boilers has not been significantly affected by the wartime conditions in 2022.

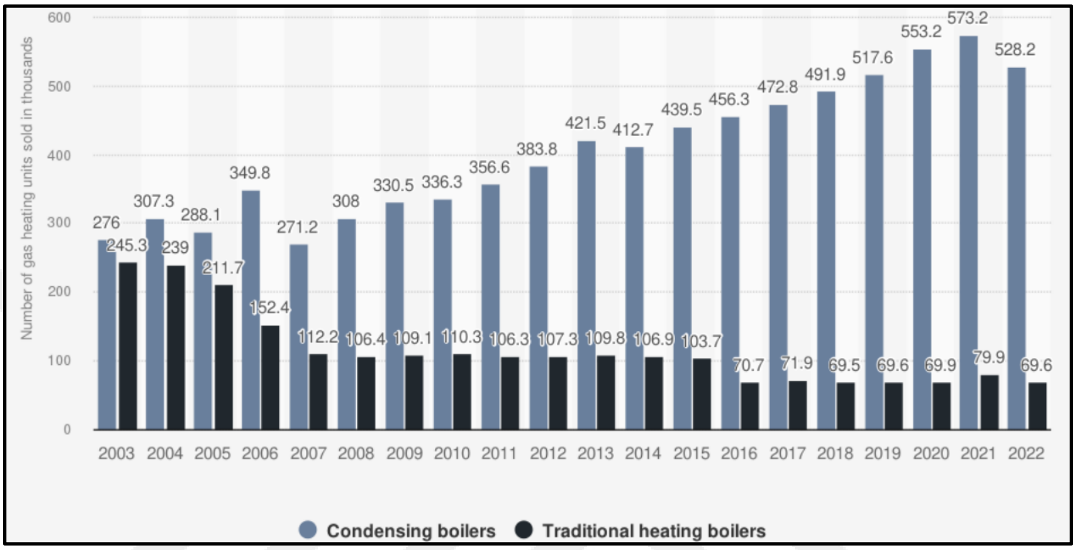


Figure 2.2 Sales of boilers units in Germany between 2003 and 2022 (in 1,000s) (BDH, 2023)

As the use and purchasing trends of gas-fired boilers continue, consumers also desire more efficient appliances. In 2018, the ErP (Energy Related Products) directive was adopted, requiring all countries fully compliant with European directives to adhere to it. Although detailed research for Türkiye is lacking, this relevant directive was implemented in the country as of 2019. As a country subject to European directives, the UK can provide valuable insights. Figure 2.3 demonstrates a significant increase in sales of condensing boilers across all countries adhering to these directives.

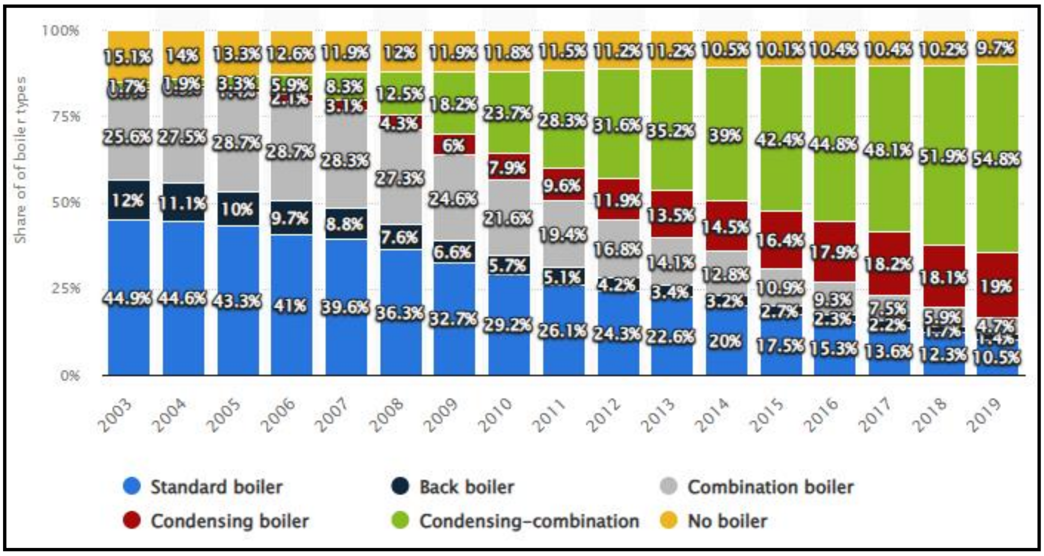


Figure 2.3 Boiler types in England between 2003 and 2019 (UK, 2020)

When considering Europe as a whole, we can see from Figure 2.4 that although there has been a decrease in gas consumption since 2022, it has not been a significant one. This suggests that gas-burning devices will continue to be used for many years to come.

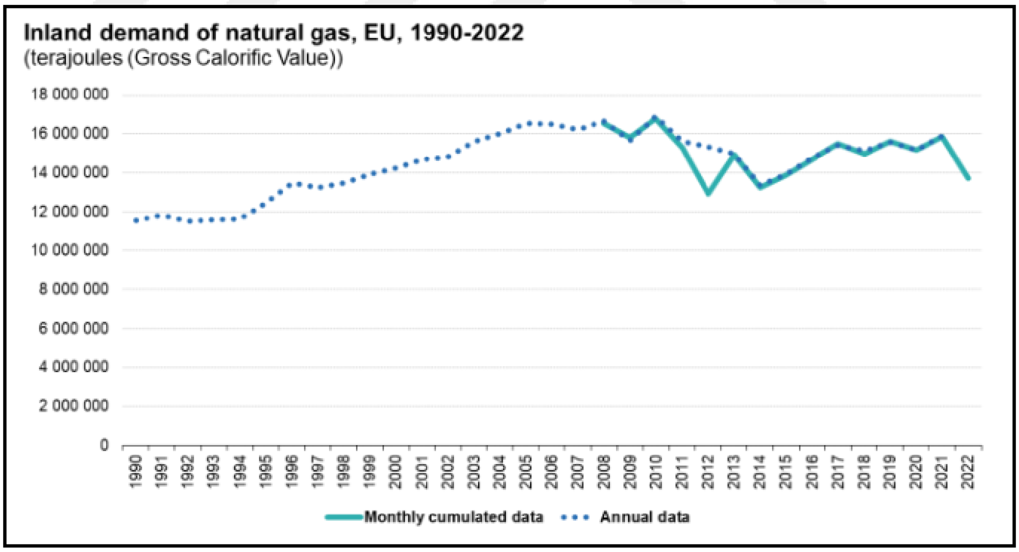


Figure 2.4 Gas consumption statistics in Europe (Eurostat, 2023)

Examining the supply-demand balance, Figure 2.5 shows the number of boilers produced in Türkiye between 2018 and 2022, which is the focus of our research. The data indicates a proportional increase in demand for boilers alongside the supply.

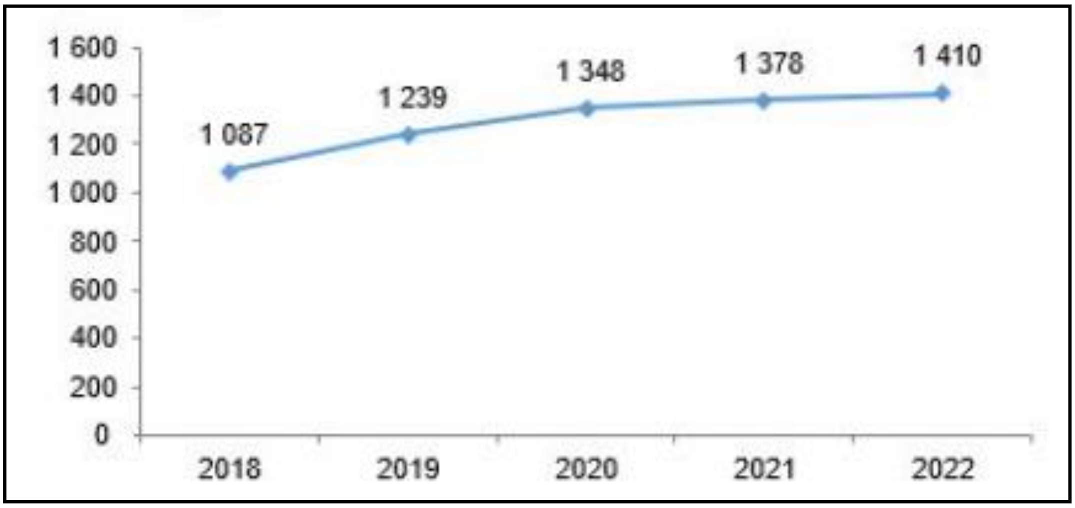


Figure 2.5 Production of combi boiler in Türkiye from 2018 to 2022 (in 1,000s) (TUIK, 2022)

Gas subscription numbers in Türkiye are regularly increasing every year, as seen in Figure 2.6. The increase in the number of subscriptions will also affect total consumption and efficiency will be a more important topic than ever.

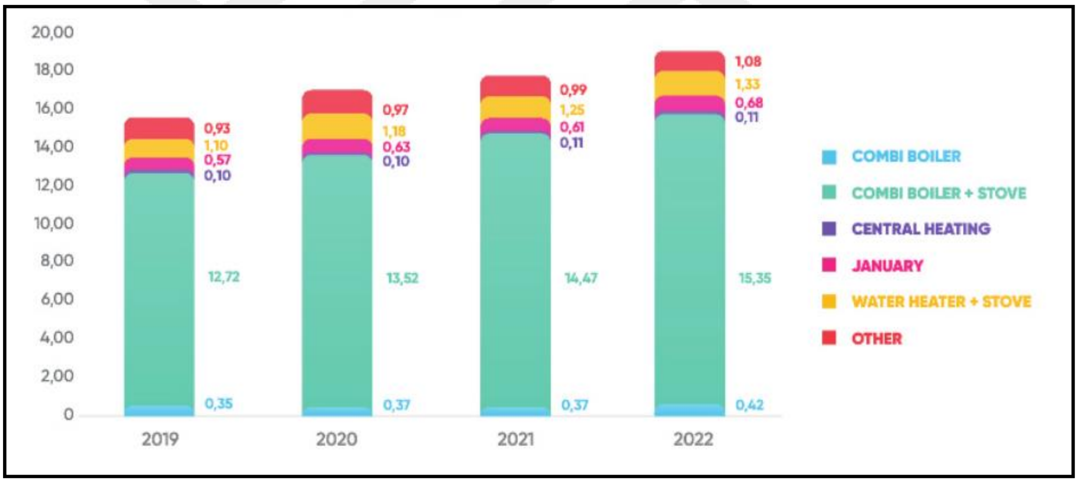


Figure 2.6 Subscription type (million) for the years 2019-2022 (Gazbir, 2022)

2.2 OpenTherm Compatible Combi Boilers: Current Models in Türkiye

Our range of boilers is equipped with the advanced OpenTherm protocol modulation, which sets a new standard in the control and efficiency of heating systems. We embrace this protocol to enhance the performance of our boilers, providing users with unparalleled control and comfort. OpenTherm technology enables precise and dynamic communication between the thermostat and the boiler, optimizing energy usage and maintaining a consistently comfortable indoor environment. Our boilers go beyond conventional control methods by adopting OpenTherm's modulating capabilities, enabling smarter and more responsive heating solutions. Experience the future of heating with our OpenTherm-enabled boilers, where efficiency meets innovation for a more sustainable and comfortable living space.

The following list includes the most popular boilers in Türkiye that are OpenTherm compatible. To ensure maximum coverage, we have included a wide range of devices. It is important to note that each manufacturer uses their own software language, which means that we cannot access other brands and models in the industry. However, we can still achieve efficiency through wireless sensor networks by using the on/off strategy with OpenTherm. Türkiye's well-known OpenTherm compatible combi boilers can be listed as follows:

- Bosch Condense 2000W ZWB24-1AR 24kW
- Bosch Classic Silver ZWA24-3AP 23kW
- Bosch Class 6000W
- Vaillant Ecotec Pro
- Vaillant Exclusive
- Vaillant Plus
- Vaillant Pure
- Viessmann Vitodens 100W WB1A/WB1B/WB1C
- Viessmann Vitodens 100W B1HA/B1KA
- Viessmann Vitodens 200W WB2B/WB2C
- Ferroli i25/i29
- Ferroli Bluehelix RRT 24C/28C/34C
- Ferroli Bluehelix Tech RRT 18S/28S/30S

2.3 The Energy-Related Products (ERP)

The Energy-Related Products (ERP) Directive is a regulatory framework in Europe designed to regulate energy usage and environmental impacts. It encompasses various product categories and aims to enhance the energy efficiency of products, promoting energy savings and environmental sustainability in the design, production, and usage phases. The Energy Related Products (ERP) directive establishes energy labelling requirements for products with specific energy usage and provides manufacturers with standards for this labelling. Additionally, it restricts the introduction of products that do not comply with specific energy requirements to the market. According to the European Commission (2023), the ERP directive provides the following advantages through these control mechanisms: energy savings. The ERP directive encourages energy savings by defining energy efficiency standards for products. Energy labelling offers consumers transparent and comparable information about product energy performance, empowering them to prefer more energy-efficient products. Increasing energy efficiency results in decreased energy consumption, contributing to a reduction in environmental impacts. Figure 2.7 shows the energy label for the Bosch Condens 2000W combi boiler, as energy labelling is mandatory for such boilers. Please refer to the explanations below the label for further information.

1. Manufacturer name or brand.
2. Model name, model description and model number.
3. Space heating function and DHW.
4. Energy efficiency class.
5. Sound power level.
6. DHW efficiency class.
7. Nominal output of heat.
8. EU Directive first validity date.
9. EU Directive related number.

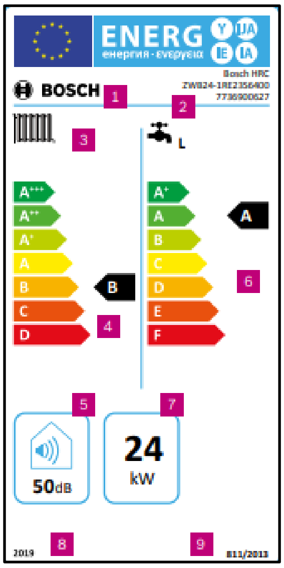


Figure 2.7 Bosch Condens 2000W combi boiler energy labelling (Bosch, 2017)

The ERP directive covers a range of energy-related product categories in European Union countries. Its objective is to establish standards that enhance the energy efficiency of products and encourage sustainable energy consumption. The directive communicates information to manufacturers and consumers through energy labelling, which is crucial in fostering a culture of sustainable energy consumption.

CHAPTER THREE
METHODOLOGY & ANALYSIS

3.1 Internet of Things

Recent technological advancements have enabled electronic devices to communicate and share data directly, either individually or by establishing an ecosystem. This has led to the emergence of the Internet of Things (IoT), which refers to the ability of electronic devices to communicate and exchange data through various network structures and protocols. When conducting thesis work, it is important to focus on appropriate methodologies and observe consumer trends.

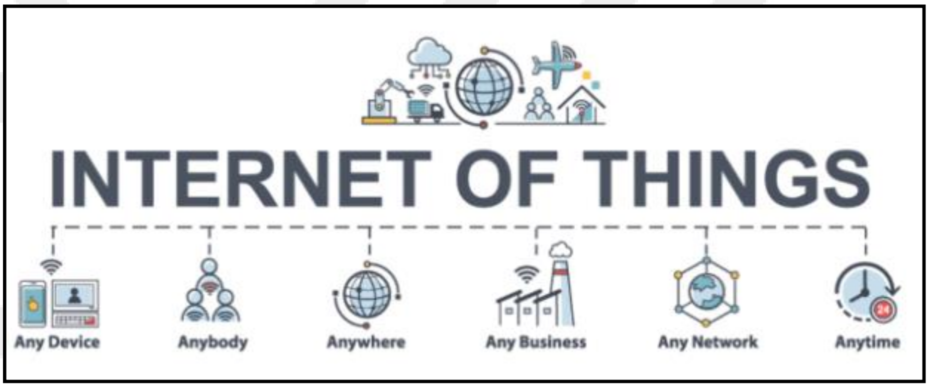


Figure 3.1 Internet of things (Smartrek, 2023)

The use of applications has expanded into various domains, as shown in Figure 3.1, including security, special tracking, agriculture, electronic metering, tech cities, and intelligent homes. This concept has emerged due to our increasingly interconnected world. The range of applications extends from smartphones, tea makers, and dishwashers to headphones, LED lighting, wearable electronics, and other items capable of internet connectivity at the flick of a switch.

The concept is also present in machine-to-machine communication, as seen in mining through sensor networks, subterranean construction, snow level monitoring, and smart metering, among other examples. Gartner predicts that by 2020, the number of installed devices will surpass twenty billion. The IoT's impact on our daily lives will undoubtedly be significant with the impending increase in connected devices. The IoT ecosystem can include various smart electronic devices with connection capabilities. Figure 3.2 illustrates the differentiation between industry and consumer devices.

In various fields, including smart homes, ecosystems, urban landscapes, healthcare, agriculture, and livestock management, as well as industrial and military applications, we are faced with an increasing number of these devices (Gartner, 2014). The purpose of using IoT in this thesis is to support the consumer side and bring this technology to homes by leveraging developments from other sectors.

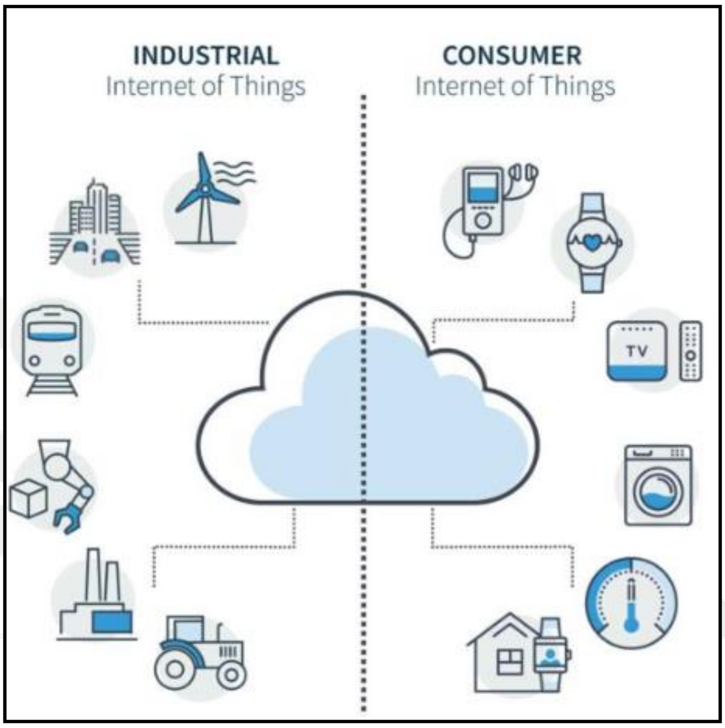


Figure 3.2 Industrial and consumer sides of internet of things (Smartrek, 2023)

The text demonstrates that all three fundamental components can be utilized in a domestic heating system. It is important to note that technical abbreviations should be explained when first used. As per insights provided by Forrester, the potential for driving business value through IoT unfolds in three distinct dimensions (Forrester, 2021). Enhancing services, operations, or products by leveraging third-party IoT customers and contextual data to elevate physical processes through enhanced information and digital automation.

Forrester's report provides strategic recommendations to guide companies towards success in the realm of IoT. The report includes a few noteworthy suggestions (Forrester, 2021), such as crafting comprehensive IoT design strategies and expanding the scope beyond the initial optimization advantages derived from integrating IoT into operational processes. It also recommends initiating the journey with a focus on customer experience, subsequently influencing internal operations. Identifying IoT opportunities for consumption involves understanding the points at which user journeys intersect with IoT-enabled assets or environments. Furthermore, the proliferation of devices connected through the IoT, as depicted in Figure 3.3, continues to increase worldwide. This highlights the importance of focusing on IoT. As demands continue to rise, providing heating to consumers remains a crucial need. Therefore, it is possible to deliver the thesis to a wider audience.

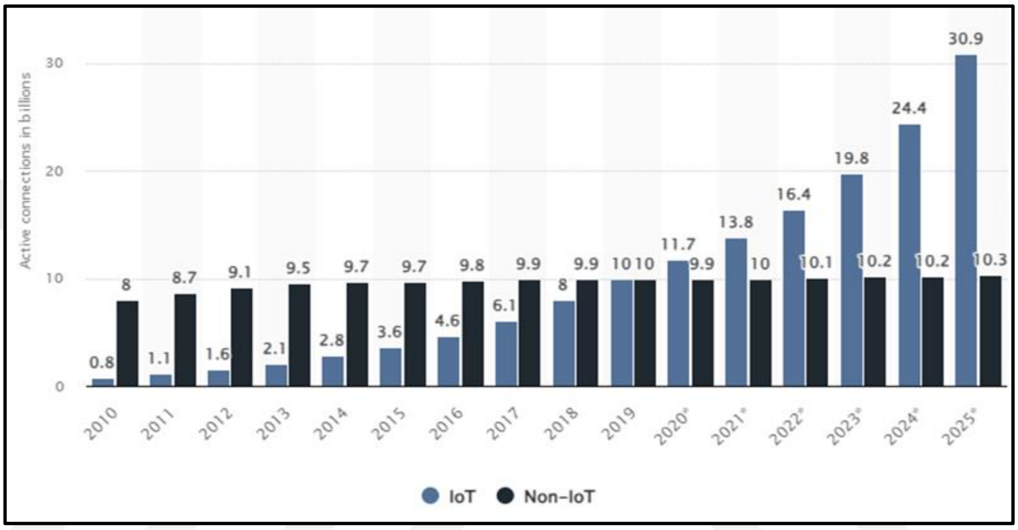


Figure 3.3 IoT and non-IoT active devices in World between 2010 and 2025 (IoT Analytics, 2020)

3.2 Communication Protocol Analysis

In an IoT ecosystem with limited hardware capabilities, the importance of the communication protocol has been highlighted due to factors such as increased communication traffic, higher power consumption, and insufficient processing, memory, and storage capacities. As a result, popular network protocols such as MQTT, AMQP, and CoAP have emerged to tackle these challenges. Table 3.1 illustrates some basic comparisons among themselves.

Table 3.1 Basic comparisons of MQTT, AMQP and CoAP (Silva et al., 2021)

	MQTT	**AMQP**	**CoAP**
Abstraction	Publish/Subscribe	Publish/Subscribe	Request/Reply
Structure	Broker Depended	B2B/Broker Depended	B2B Depended
Transports	TCP	TCP	UDP
Subscription Control	Hierarchical	Exchange Queues	Multicast
Security	SSL	TLS	DTLS

3.2.1 Constrained Application Protocol

The Constrained Application Protocol (CoAP) is a service layer protocol designed for resource-limited, low-power sensors and devices that operate in environments with unreliable network connections. CoAP is particularly prevalent in scenarios characterized by a multitude of sensors and devices, and it stands out as a leading communication protocol in the realm of the IoT. CoAP's popularity is due to its ability to bridge the gap between HTTP and resource-constrained devices, making it ideal for applications such as advanced metering and distributed intelligence. It operates on a client/server model and leverages REST principles, which enhances its interoperability across diverse systems. CoAP's design is optimized for resource consumption, considering the limitations of constrained devices such as battery life, memory, and storage. Communication between clients and servers is facilitated through four primary messages: GET, PUT, POST, and DELETE, using UDP as its transport layer. CoAP's lightweight architecture makes it a promising protocol for embedded devices, enabling efficient communication in resource-scarce environments (Silva et al., 2021).

3.2.2 Advanced Message Queuing Protocol

The Advanced Message Queuing Protocol (AMQP) is a communication protocol that facilitates reliable and efficient message exchange between applications. Its reliability is a key advantage, as AMQP ensures consistent message delivery even in the presence of network failures or system errors. The protocol is also known for its efficiency, optimizing message transmission and processing to enhance overall performance. AMQP has the advantage of interoperability, allowing seamless integration among different systems and programming languages. Additionally, it offers flexibility in message routing, queuing, and delivery, enabling adaptable communication patterns tailored to specific requirements. From a security standpoint, AMQP provides built-in features such as encryption and authentication to ensure the confidentiality and integrity of transmitted data.

However, AMQP also has some disadvantages. One challenge is its complexity. Implementing and managing AMQP-based systems may require specialized knowledge and expertise, which can increase overall complexity. Additionally, the additional features and mechanisms provided by AMQP may introduce overhead in terms of processing and resource utilization, potentially impacting performance, especially in high-throughput environments. Scalability is also a concern. Careful architecture design may be necessary to scale AMQP-based systems to handle large volumes of messages or increased load. Additionally, dependency on specific AMQP implementations or vendors may result in vendor lock-in, limiting flexibility and hindering interoperability with other systems. Despite these drawbacks, AMQP is widely adopted in various applications and industries due to its reliability, efficiency, and security benefits (Vinoski, 2006).

3.2.3 Message Queuing Telemetry Transport

MQTT, or Message Queuing Telemetry Transport, is a communication protocol designed for the dynamic landscape of the Internet of Things (IoT). Its lightweight architecture makes it an ideal choice for devices operating in resource-constrained environments, which are ubiquitous in IoT ecosystems. MQTT can be used in individual heating systems (Nuratch, 2018).

MQTT is a protocol that is well-suited for IoT applications due to its ability to facilitate streamlined data transmission. It achieves this by minimizing data overhead, allowing devices with limited processing power and bandwidth to communicate with ease. Additionally, MQTT has minimal impact on bandwidth and energy resources, making it an energy-efficient option for IoT devices. In IoT scenarios, devices often rely on battery power or operate within restricted bandwidth constraints. It is important to note that this information is objective and free from ornamental language.

MQTT's connection management system allows devices to easily establish, disconnect, and automatically re-establish connections in the face of disruptions, providing a resilient and persistent communication channel. Furthermore, MQTT ensures message delivery. MQTT provides flexible options for ensuring reliable message delivery through various QoS levels. This feature is crucial in IoT applications where data transmission integrity is of utmost importance. MQTT's adaptability in protocol implementation is customizable, empowering developers to tailor it to specific IoT use cases, making it essential in diverse IoT environments with various device types and communication requirements. MQTT includes strong security measures, such as TLS/SSL encryption, to protect data exchanged between devices in IoT ecosystems. It is also designed to efficiently manage a growing number of devices within an IoT network while being resource efficient. According to MQTT.org (2019), this makes it ideal for environments where optimal resource utilization is a primary concern.

MQTT was compared to other wireless technologies because it has more libraries and content in microcontroller applications and is suitable for continuous broadcasting in existing home infrastructure.

3.3 The Position of MQTT Among Other Technologies

In comparison to other popular IoT technologies such as Zigbee, Bluetooth and Wi-Fi, MQTT emerges as the frontrunner when it comes to balancing energy efficiency, bandwidth utilization and reliable communication. Although Zigbee may excel in mesh networking for smart home devices, and Bluetooth's Low Energy variant targets specific applications like sensors and headphones (Miller et al., 2000), Wi-Fi provides high bandwidth but at the cost of increased power consumption (Ding et al., 2018).

In essence, MQTT's lightweight design, coupled with its focus on reliability, security, and adaptability, makes it a compelling choice for IoT applications, particularly in the context of smart home heating systems. Its ability to handle diverse IoT requirements seamlessly makes it an indispensable tool for developers crafting robust and efficient IoT solutions. The reliability of smart home sensor systems was analyzed in the face of competing failures. Given the challenges associated with ZigBee and Bluetooth devices, a shift towards MQTT and Wi-Fi technologies is advocated.

Controlling home heating systems, particularly gas-fired combi boilers, can be done more effectively by following these methods. Unlike ZigBee and Bluetooth setups, which are dependent on gateways, MQTT and Wi-Fi provide direct network connectivity, reducing the risk of functional failures associated with gateway breakdowns. This approach reduces the system's vulnerability to isolated sensor failures, resulting in a more robust and reliable control mechanism. The use of MQTT and Wi-Fi technologies presents a promising opportunity to improve the efficiency of smart home sensor systems, addressing the limitations of relying solely on ZigBee and Bluetooth devices (Wang et al., 2022).

Bluetooth, standardized under IEEE 802.15.1, is primarily designed for cable-free communication between mobile and other devices over short distances. It is known for its efficiency, low power consumption, and reliable transmission of digitized voice and data across the 2.4 GHz ISM band without requiring a clear line-of-sight. Bluetooth uses radio waves for communication. Operating within the frequency range of 2.400 to 2.483 GHz with a 1 MHz band, Bluetooth devices can operate in dual modes, supporting both BR/EDR and BLE, or single mode, exclusively supporting Bluetooth low energy. The energy-saving nature of BLE makes it a preferred choice for many Bluetooth devices in IoT applications. For single-mode BLE devices, the protocol stack is organized into three layers: controller, host, and application. The protocol stack is composed of foundational constituents that break down into various sub-layers to provide the necessary functionality (Bluetooth.com, 2023).

ZigBee is a cost-effective wireless network technology based on the IEEE 802.15.4 standard. It is interoperable, standards-based, and suitable for low data rate requirements, low energy consumption, and enhanced security. This allows nodes to explore alternative routes and dynamically adapt to failures. ZigBee is a wireless solution within the IoT domain that boasts a self-optimizing network structure. Its decentralized architecture makes it a robust choice for wireless sensor networks. ZigBee finds applications in diverse sectors such as alarm systems, smart homes, building-based automation, smart cities, transportation, local management, and patient condition control systems (Farahani, 2008).

ZigBee operates at varying speeds and is particularly effective in scenarios that require low data rates, cost-effectiveness, and extended battery life, making it ideal for battery-powered devices. ZigBee devices predominantly reside in power-saving mode, resulting in prolonged operational periods without the need for frequent battery changes. The text describes the stage textures of the OSI model, the ZigBee protocol-based stack, and the TCP/IP protocol-based stack that define ZigBee's execution of physical layer processes in accordance with the IEEE 802.15.4 protocol. The NWK plays a pivotal role in network creation, overseeing tasks such as connecting/disconnecting a network, configuring new devices, and managing coordinator and router operations. Meanwhile, the application stage, comprising APS and ZDO, houses manufacturer-defined applications. APS manages the discovery and binding services, identifies devices on the network, and facilitates message transmission between connected devices (Zigbee Alliance, 2019). Table 3.2 illustrates all comparisons.

In this thesis, energy efficiency is prioritized over other factors, therefore Wi-Fi was not chosen despite its strengths in group communication, resource management and stability. Bluetooth, on the other hand, has advantages such as low energy consumption and protocol flexibility, but it is not preferred due to its lower connection stability compared to other options and its inability to perform group communication, which is a critical issue for the thesis. Although Zigbee and MQTT are comparable in many ways, MQTT was chosen due to its lower bandwidth usage. This decision was based on the benchmarks presented in Table 3.2, as communication will be required in every room or area of the house (Wang et al., 2022). Its comparison highlights MQTT's strengths in efficient data transmission, low energy consumption, and reliable connection management, making it a suitable choice for various IoT applications, including smart home heating systems. However, it also has some drawbacks.

Table 3.2 Comparison table between MQTT, Zigbee, Bluetooth, and Wi-Fi (Wang et al., 2022)

Features	**Wi-Fi**	**Bluetooth**	**Zigbee**	**MQTT**
Communication Method	Point to Point	Point to Point	Mesh Networking	Publish/ Subscribe
Bandwidth Usage	High	Medium/Low	Medium/Low	Low
Energy Consumption	High	Low	Low	Low
Reliability of Connection	High	Medium/High	High	High
Assurance of Message Delivery	Yes	Yes (Bluetooth LE)	Yes	Yes (QoS Levels)
Light Weightiness of Protocol	No	Yes	Yes	Yes
State Retaining	Yes	Yes	Yes	Yes
Security	Yes	Yes	Yes (AES)	Yes (TLS/SSL)
Protocol Flexibility	Yes	Yes	Yes	Yes
Group Communication	Yes	No	Yes	Yes
Broadcasting of Message	No	Yes	Yes	Yes
Resource Management	High	Low	Medium	Low
Application Domain	Wide Application Range	Headphones, Sensors, Sound Systems	Smart Home Devices, Industrial Control	General IoT, Smart Home Systems

3.4 Examination of MQTT Protocol

Although the MQTT protocol has several commendable features, it also has some limitations and drawbacks. One primary disadvantage is its inherent reliance on the broker, which constrains the scalability of the entire system to the capabilities of the broker. This interdependence introduces a potential bottleneck, hindering the system's ability to grow beyond the limitations imposed by the broker (Corner et al., 2019). In an automation system, the broker serves as a centralized hub for data exchange. However, the centrality of the broker also makes it vulnerable to being a single point of failure. The broker is typically directly connected to a power source, often a wall socket, which introduces a precarious scenario. It is important to note that this is a potential vulnerability and not a certainty. Therefore, it is crucial to ensure that the broker is adequately protected against potential failures. Offline brokers can disrupt the seamless functioning of the entire system when devices attempt to transmit or retrieve data (Minteer, 2017). It is important to maintain integrity of meaning throughout the introduction of the system.

The master module is physically connected to the combi boiler and operates based on data received from the outdoor temperature sensor. It is important to note that the heating system will be disabled when outdoor temperatures exceed 16 ℃. The experimental section contains the relevant algorithms and codes. For this reason, we found these disadvantages to be acceptable as they did not have a fatal effect on the design implemented in our thesis.

The MQTT communication method involves several components, including the Publishing/Subscribing System, Topics, Message and Data.

3.4.1 Publishing/Subscribing System

The Publishing/Subscribing System doctrine states that a device can send a message to any topic, but the topic must subscribe to receive the message. For example, imagine a bright object sending information to a topic. If one's mobile device is aligned with the topic, it will receive the information.

3.4.2 Message and Data

A message is the exchange of information between devices, which can take various forms such as text, strings, and numbers. The format of a message is tailored to the specific application. The message content utilized in our thesis includes temperature, humidity, and motion sensor data, as well as on/off commands for the solenoid radiator control. This data is categorized based on the area it occupies. It is important to note that every MQTT Control Packet includes a fixed header, as described in Table 3.3.

Table 3.3 MQTT fixed header (MQTT.org, 2019)

Bit	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
byte one	Control Packet of MQTT				Flags Specific for Each Type			
byte two	Remaining Length							

3.4.3 Topics

Topics are the titles of the modules available in each region. When a broadcast is made from the bedroom module, the master module that wants to access that broadcast must subscribe to it using a specific topic name. This ensures that the information transmitted by the slave modules is not confused.

3.5 Language and Communication Methods of MQTT

Analyzing the MQTT protocol, along with other protocols, on a microcontroller poses considerable challenges. Therefore, it demands a more extensive development effort compared to implementation on a computer. As embedded developers, it is inevitable that we navigate through intricate implementation processes. Fortunately, comprehensive documentation equips us with essential knowledge before embarking on firmware construction.

3.5.1 Establishing Internet Network Connection

Establishing a connection to the internet network is a relatively uncomplicated process. For the Wi-Fi module, providing the SSID and PASSWORD is sufficient. However, for the Ethernet Controller chip, the key is to connect the RJ45 cable to the board. To execute this protocol on a microcontroller, you need to formulate a suitable command, send it to the Wi-Fi module (or ethernet controller chip), and wait for confirmation of a successful connection before proceeding to the next phase.

3.5.2 Connecting to MQTT Server/Broker

Before connecting to the MQTT server/broker, it is essential to have the server's IP address and connection port. For instance, the IP address 198.38.24.171 and Port 8883 for MQTT over TCP/IP are crucial details. No specialized procedures are required at this stage. Simply craft a connection command by specifying the IP and Port, and then transmit the command to the Wi-Fi based module or Ethernet device.

3.5.3 Client Initiates Connection to the Server/Broker

After establishing network and server connections, it is necessary to prepare and send the CONNECT package to the server. The MQTT protocol does not require a username and password. A clean session is mandatory, QoS is set to zero, no Wills are necessary (0x02), and the remaining length is fixed at 16 bytes. Note that the CONNECT package consists of a sequence of hexadecimal (or decimal) numbers that can be organized into a simple array of bytes, as shown in Table 3.4, and then transmitted to the Wi-Fi module or Ethernet Controller chip. After sending this package to the server, the reception of the CONNACK indicates the server's readiness to proceed to the next stage.

Table 3.4 MQTT CONNECT fix header (MQTT.org, 2019)

Bit	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
Byte one	Control Packet of MQTT				Reserved			
	0	0	0	1	0	0	0	0
Byte two	Remaining Length							

3.5.4 Subscribing to Preferred Topics

The SUBSCRIBE packet contains the process of subscribing, which is designed to establish one or more subscriptions with the server. Each subscription expresses the client's interest in specific topics. The packet also defines the QoS level for the server to forward application messages to the client. The remaining length in this packet is fixed at 8 bytes. Similar to the construction of the CONNECT package, these hexadecimal numbers convert smoothly into an array of bytes, ready for transmission to the server.

3.5.5 Broadcasting Messages to a Topic

The client can send messages to the server at any time using the PUBLISH package, as described in Table 3.5. In this scenario, the client sends the message '12.34' to the topic 'ecc.' Upon receiving the message, the server distributes it to other clients subscribed to the same 'ecc' topic. The MQTT communication network enhances the collaborative exchange of information in a dynamic process that showcases its interconnected essence.

Table 3.5 MQTT PUBLISH fix header (MQTT.org, 2019)

Bit	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
Byte one	Control Packet of MQTT				Flag	QoS Level		Retain
	0	0	1	1	X	X	X	X
Byte two	Remaining Length							

3.5.6 PING Request

The PING packet is a valuable component in MQTT communication. It serves as a means for the client to signal its vitality to the server during periods of inactivity and to ascertain the continued vitality of the server. Additionally, the PING packet is instrumental in scrutinizing the network connection status. It consists of just three bytes, comprising 0xC0 followed by 0x00.

3.6 OpenTherm Protocol

OpenTherm is a communication protocol designed for modulating the control of heating systems, particularly boilers. It enables bidirectional exchange of information between the heating device and the thermostat, fostering dynamic interaction to achieve more precise temperature control. The protocol facilitates modulation of the combustion power within the heating appliance, contributing to enhanced operational efficiency and energy conservation. Figure 3.4 illustrates the use of a two-way communication framework. OpenTherm enables flexible adjustment of parameters such as water temperature, circulation pump speed, and combustion power, providing a versatile means of system control.

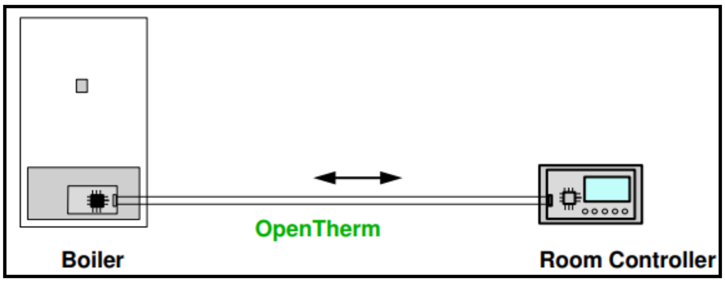


Figure 3.4 OpenTherm basic controlling schematic (OpenTherm, 2003)

Its standardized format ensures compatibility among diverse products from different manufacturers, establishing OpenTherm as a widely accepted and adopted heating control standard in Europe. OpenTherm optimizes heating system performance through nuanced modulation and efficient communication between components. (OpenTherm, 2023)

Not every manufacturer allows access to all channels, so even if the combi boiler produced by the manufacturer is compatible with the OpenTherm language, it provides control only in the permitted areas. The studies in the thesis used the basic parameters listed in Table 3.6, which are important for the research.

Table 3.6 OpenTherm master crucial id list (OpenTherm, 2003)

ID	Description
ID0:HB0	Master State: Enable Central Heating (CH)
ID0:HB3	Master State: Active Outdoor Thermal Comfort (OTC)
ID0:LB3	Slave State: Flame Status
ID1	Water Flow Temperature of CH
ID27	Outside Temperature
ID3:HB4	Master Configuration: Pump Control
ID5:LB	OEM Fault Code

3.7 Components

This section explains the components used in the system installation and those that will collaborate with it. It includes microcontrollers, sensors, valves, a gas-fired combi boiler, and all other components necessary to complete the system in the house.

3.7.1 NodeMCU

NodeMCU is a widely recognized and affordable product worldwide due to its Wi-Fi hotspot, making it a powerful solution for small projects. It has cost friendly price as 4$ in microcontrollers (Amazon, 2024). It is also compatible with the Arduino library, making it a suitable choice for thesis study. Figure 3.5 illustrates NodeMCU, an open-source firmware and development board designed for IoT applications. NodeMCU is based on the Lua programming language and designed to meet the dynamic requirements of IoT projects. Kashyap et al. (2018) emphasized the seamless compatibility between MQTT and NodeMCU in their study. It includes firmware specifically crafted to operate on the ESP8266 Wi-Fi SoC developed by Espressif Systems. The module's hardware is intricately designed around the ESP-12 module, providing a durable foundation for IoT developers and enthusiasts to seamlessly integrate wireless connectivity and Lua-based programming into their innovative projects (Espressif, 2023).

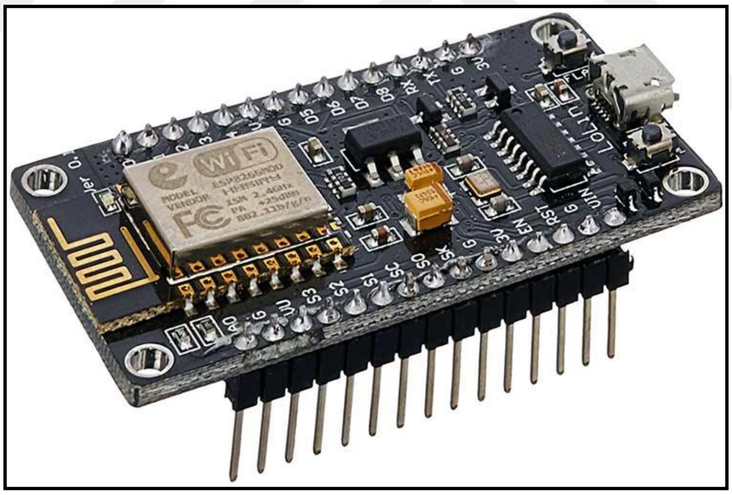


Figure 3.5 NodeMCU-ESP8266 (Espressif, 2023)

This thesis study utilized seven NodeMCU, with six of them operating as slaves and one serving as the master, connected to the combi boiler via OpenTherm Adaptor.

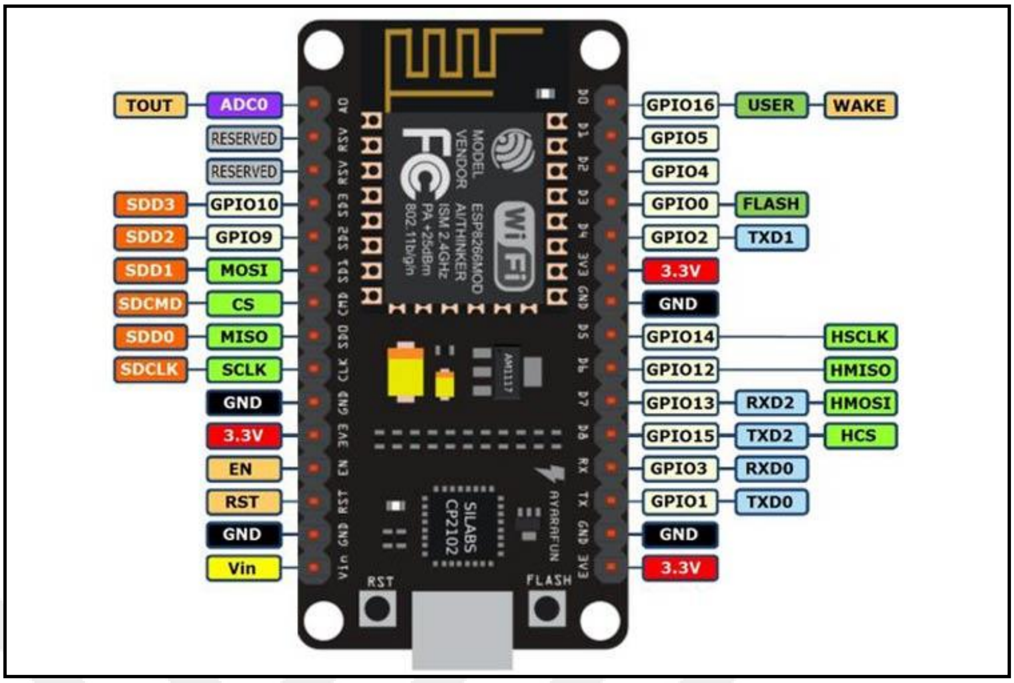


Figure 3.6 NodeMCU-ESP8266 pinouts (Espressif, 2023)

These pinouts for the NodeMCU system's General-Purpose Input/Output Interface (GPIO), which has a maximum of seventeen pins. These pins are versatile and can be configured through firmware settings. Table 3.7 lists each GPIO, which is adaptable and supports internal pull-up (except for XPD_DCDC, which is configured with internal pull-down).

Table 3.7 Pin definitions of GPIOs (Espressif, 2023)

	Symbol	**Minimum**	**Maximum**	**Unit**
Input Low Voltage	V_{IL}	-0,3	$0.25xV_{IO}$	V
Input High Voltage	V_{IH}	$0.75xV_{IO}$	3.3	V
Input Leakage Current	I_{IL}		50	nA
Output Low Voltage	V_{OL}		$0.1xV_{IO}$	V
Output High Voltage	V_{OH}	$0.8xV_{IO}$		V
Input Pin C Value	C_{pad}		2	pF
VDD_{IO}	V_{IO}	1.8	3.3	V
Max. Power Current	I_{MAX}		12	mA
Temperature	$T_{Ambient}$	-40	125	^{0}C

The pins have multiple functions and can be used as input for software registers, trigger interrupts based on input edges or levels, initiate level-based wakeup interrupts, operate as open-drain or push-pull output drivers, or serve as output sources derived from software registers. These multifunctional pins share duties with I2C, I2S, UART, PWM, IR Remote Control, and other features. The soldering pads for bidirectional and tri-state data I/O include both data input and output control buffers. Furthermore, the I/O configurations can be set to specific states that persist over time. For example, to reduce chip power consumption, all data input and output enable signals can be configured to a low-power state. Specific states can be transferred to the I/O, and when the I/O lacks external circuit power, it retains its last-used state. The pins' state-remaining feature generates positive feedback, so external driving power must exceed this feedback, even if the required driving power is below 5uA.

- GND: Grounds pins.
- V_{in}: External power supply.
- EN, RST: Resetting microcontroller.
- A0: Using measure analog voltage between 0V and 3V3.
- GPIO1 to GPIO16: General purpose input and outputs pins.
- SD1, CMD, SD0, CLK: SPI communication pins.
- TXD0, RXD0: UART0 interface.
- TXD1, RXD1: UART1 interface and point of uploading firmware.

3.7.4 OpenTherm Adaptor

Integrating OpenTherm with microcontrollers such as NodeMCU can be challenging due to the discrepancy in voltage levels. These platforms usually operate at lower voltage levels than traditional OpenTherm-compatible heating systems. It acts as an intermediary, translating the lower voltage signals from microcontrollers to levels compatible with OpenTherm standards, ensuring smooth data exchange. The voltage levels of NodeMCU may not be compatible with OpenTherm standards, making the adapter indispensable. The adapter not only translates voltage disparities but also safeguards signal integrity, fostering secure integration between intelligent microcontrollers and advanced heating systems. Table 3.8 displays the costs of the materials used for the US dollar realization. The circuit can be constructed for a total of 1.45 US dollars (Melnyk, 2018).

Table 3.8 The cost list of OpenTherm Adaptor (Melnyk, 2018)

Name	**Price**	**Total Price**
Opto-coupler PC817 x 2	0.2$	0.4$
BC858A PNP Transistor	0.1$	0.1$
Diode 1N4148 x 4	0.1$	0.4$
Zener Diode 4.7V	0.1$	0.1$
Zener Diode 15V	0.1$	0.1$
Zener Diode 4.3V	0.1$	0.1$
One-fourth-Watt 5% Resistor 100 Ohm	0.01$	0.01$
One-fourth-Watt 5% Resistor 220 Ohm	0.01$	0.01$
One-fourth-Watt 5% Resistor 330 Ohm x 2	0.01$	0.02$
One-fourth-Watt 5% Resistor 1k5 Ohm	0.01$	0.01$
PCB Single Side	0.2$	0.2$

The OpenTherm adapter, illustrated in Figure 3.7, plays a critical role in harmonizing diverse voltage requirements, and facilitating a seamless connection between modern microcontrollers and established heating infrastructures (Melnyk, 2018). The mounted PCB is shown in Figure 3.8.

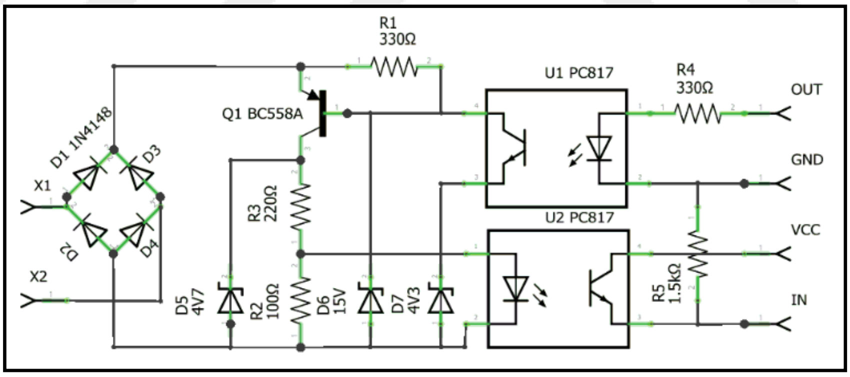


Figure 3.7 OpenTherm adaptor circuit schematic (Melnyk, 2018)

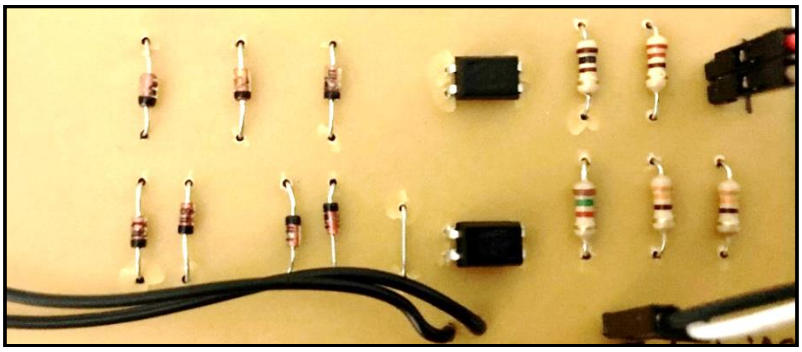


Figure 3.8 OpenTherm adaptor (Personnel Archive, 2023)

The voltage range at the thermostat inputs of combi boilers typically falls between 12-18V. To prevent potential damage to the Arduino and ensure control over signals with voltage and current, it is recommended to use an adapter. The correct wiring configuration involves connecting the output pin of the OpenTherm Adapter to the input pin of the ESP8266, and vice versa, connecting the input pin of the OpenTherm Adapter to the output pin of the ESP8266. When configuring the output pin of the controller, it is crucial to confirm that the assigned input pin supports interrupts. For the ESP8266, interrupts can be assigned to any GPIO pin except GPIO16. It is important to note that GPIO6-GPIO11 are usually reserved for interfacing with flash memory ICs on most ESP8266 modules. Therefore, it is advisable to avoid assigning interrupts to these pins to ensure smooth functionality. To establish a reliable connection between the OpenTherm Adapter and the ESP8266, it is essential to carefully consider GPIO pin selection.

3.7.5 PIR Sensor

PIR stands for Pyroelectric Infrared Radial Sensor or Passive Infrared Sensor. It is an electronic device that detects changes in infrared light over a specific distance and produces an electrical signal when it detects an infrared signal. The PIR sensor module, illustrated in Figure 3.9, comprises two main components: an infrared-sensitive crystal and the processing circuit. PIR sensors are ideal for indoor use, especially in household rooms, due to their practicality. They have a typical range of 20 to 30 feet and a detection angle of approximately 110 ℃, effectively covering the intended area. It is important to note that environmental conditions, ambient temperature, and the size of the moving object can affect the effective range. Specialized PIR sensors may provide different coverage patterns to meet specific requirements. For instance, some sensors are designed for long-range outdoor use, while others are intended for more confined indoor spaces.

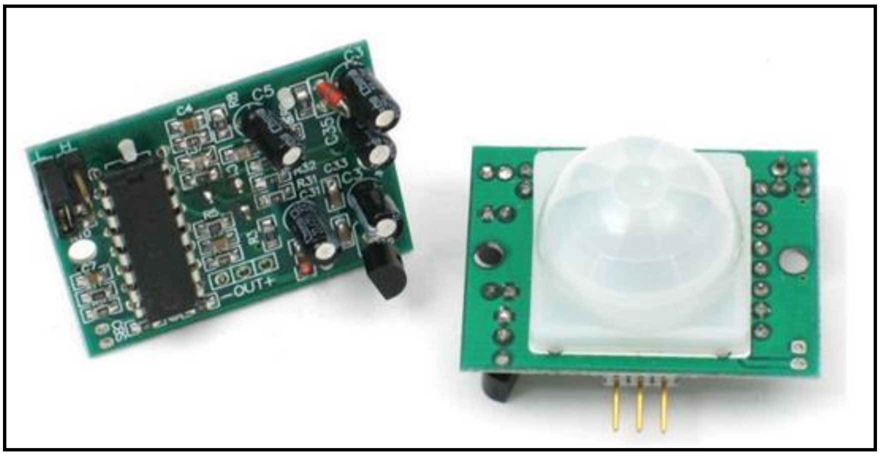


Figure 3.9 PIR motion sensor HW416 (Adafruit, 2012)

The pyroelectric infrared sensor operates by utilizing the property of its material to change polarization in response to temperature changes. In this bellowing project, a PIR sensor is used to monitor room entrances and exits and generate a temperature algorithm. According to Esfahani's (2016) study, the reliability of the sensor was found to be 96%. T_o infer occupancy during a 10-hour observation period, the standard deviation of motion values was analyzed in 30-second time windows, representing motion intensity. The blue line represents the ground truth occupancy, while the green line depicts the motion threshold set at $T_o = 17.25$. According to Esfahani (2016), our specific deployment achieved a 96% accuracy rate in detecting occupancy which is illustrated in Figure 3.10.

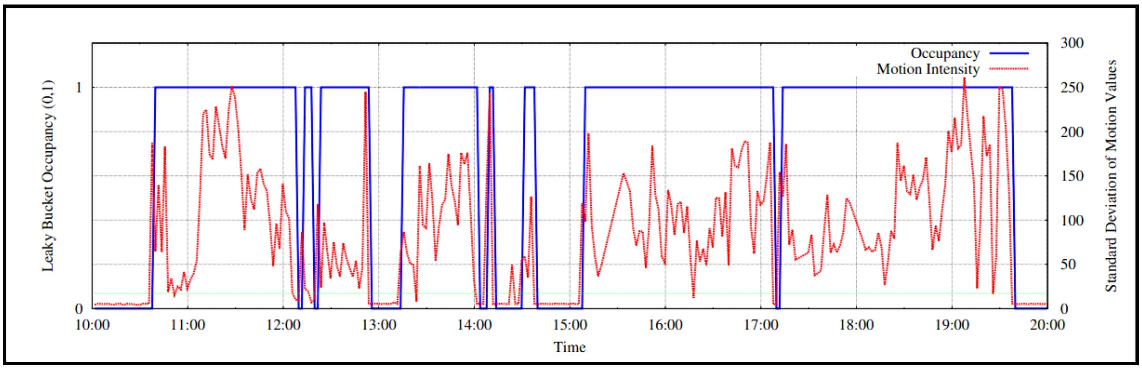


Figure 3.10 An example of occupancy inference (Esfahani, 2016)

These sensors utilize dual or paired sensing elements to detect infrared (IR) signals in two stages, which enhances reliability by mitigating the impact of undesired temperature variations during the existing electromagnetic interference (EMI) stage. This two-step sensing process contributes to the overall stability of the sensor, enabling it to specifically detect IR signals emanating from human presence. The PIR sensor detects when a person or object approaches it by alternately affecting its two sensing elements with radiation. This interaction triggers the sensor's output, generating a sequence of ON/OFF or high and low pulses, as shown in the waveform below. The sensor has two distinct timeouts. The first, referred to as 'T_X', determines how long the LED stays lit after motion detection. The Adafruit PIR sensors allow for convenient adjustment of this parameter through a potentiometer. The second timeout, known as 'T_i', indicates the guaranteed period during which the LED stays off when there is no motion. Changing T_i is more complex than T_x, but it is still a feasible option for those skilled with a soldering iron.

As mentioned in the datasheet, Adafruit PIR sensors have a small trim potentiometer labeled 'delay time adjust'. The circuit includes an adjustable resistor with a value of 1 Mega Ohm connected in series with a 0.01 Mega Ohm resistor. Furthermore. When the R_{Time} potentiometer is turned fully counterclockwise (to zero ohms), Tx is approximately 2500 milliseconds. Conversely, rotating the R_{Time} potentiometer entirely clockwise to 1 Mega Ohm results in Tx being around 250 seconds. Setting R_{Time} in the mid-position achieves approximately 120 seconds, offering flexibility for adjustments as illustrated in Figure 3.11. In the thesis, it was not used by the software, so it was kept near 2500 milliseconds according to Equation 3.2.

$$T_x = 24576 \text{ x } (10\text{K} + R_{Time}) \text{ x } 0.01\text{uF} \tag{3.2}$$

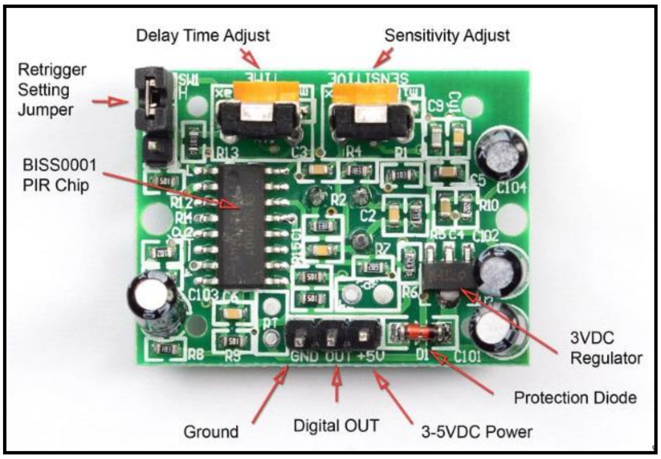


Figure 3.11 Adjustment of PIR sensor (Adafruit, 2012)

3.7.6 DHT22 Temperature and Humidity Sensor

Thesis study involves receiving data from six areas. In addition, an outdoor humidity and temperature sensor is used, bringing the total number of DHT22s to seven. Figure 3.12 displays the DHT22, which uses advanced humidity sensing technology to generate a calibrated digital signal through an exclusive digital signal collection technique. This design ensures the sensor's reliability and stability across various environmental conditions. The sensing elements are connected to an 8-bit single-chip computer. Each sensor of the DHT22 model undergoes temperature compensation and calibration within a dedicated chamber. The calibration coefficient resulting from this process is stored in One-Time Programmable (OTP) memory and referenced during sensor operation, significantly enhancing accuracy. The DHT22 is recognized for its compact size, low power consumption, and impressive transmission range of up to twenty meters, making it suitable for deployment in a diverse range of challenging application scenarios (SparkFun, 2023).

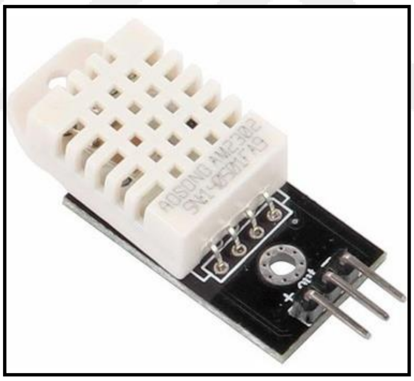


Figure 3.12 DHT22 temperature and humidity sensor (SparkFun, 2023)

Obtaining temperature and humidity data is crucial because human perception of temperature is influenced by humidity levels. Luo et al. (2019) demonstrated this relationship in Figure 3.13, which can be used to calculate the apparent temperature (AT) value. Our home system considers the AT value.

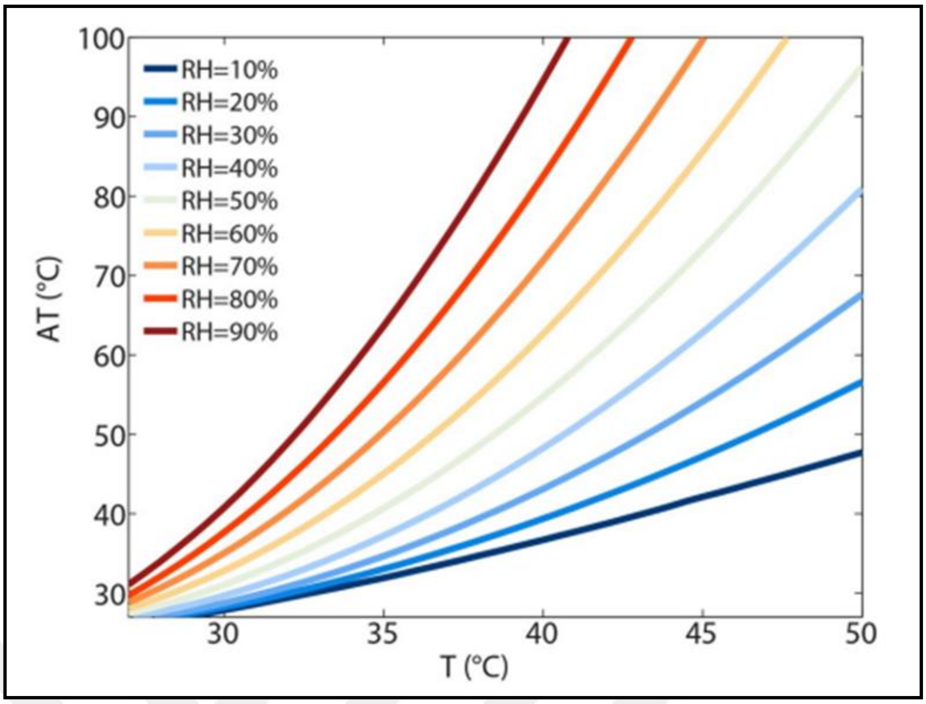


Figure 3.13 Relationship between AT, T, and RH (Luo et al.,2019)

3.7.7 Solenoid Valve

The solenoid valve shown in Figure 3.14 is used in conjunction with electronic circuits to regulate liquid flow. The valve is normally closed, but when a 12V voltage is applied to the terminals, it opens to allow liquid to pass through. It has a one-half inch NPT pipe connection. To ensure smooth liquid flow, it is necessary to apply a minimum pressure of 0.02 Mpa for optimal performance. When integrating this solenoid valve with microcontrollers, it is recommended to construct a dedicated driver circuit. The circuit should include an N-type transistor, such as the BDX53C, and a diode, such as the 1N4007. This additional circuitry improves the compatibility and control of the solenoid valve in electronic systems (Zhang, 2010).

The solenoid valve specifications are as follows: operating pressure ranges from 0.02 Mpa to 0.8 Mpa, operating temperature ranges from 1 ℃ to 75 ℃, valve opening time is less than or equal to 0.15 seconds, and valve closing time is less than or equal to 0.3 seconds. The operating voltage for this device is $12V_{DC}$, although it can also be used with 6V. The operating life is equal to or greater than fifty million open-close cycles (e-Gizmo, 2016).

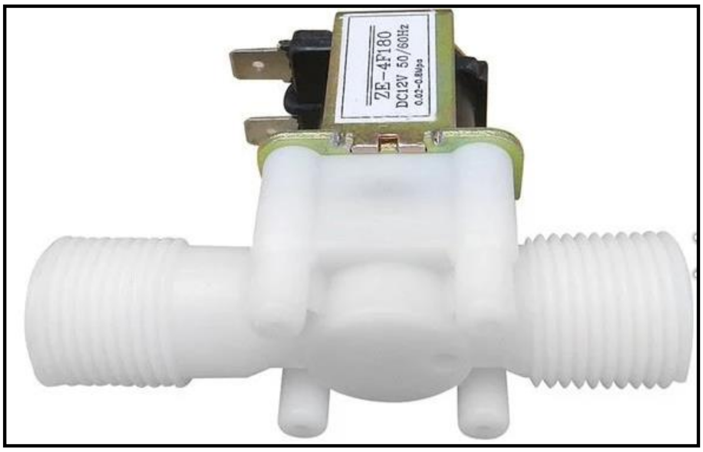


Figure 3.14 Solenoid valve ZE-4F180 DC 12V (Personnel Archive, 2023)

The NodeMCU designated as slaves are equipped with six solenoid valves that are triggered by relays, which are described in section 3.7.10. These solenoids operate on an open or close logic. Specifically, solenoids R1, R2, R3, R4, R5, and R6 are installed. Figure 3.15 displays both the solenoids and the radiators they control with a simple system diagram.

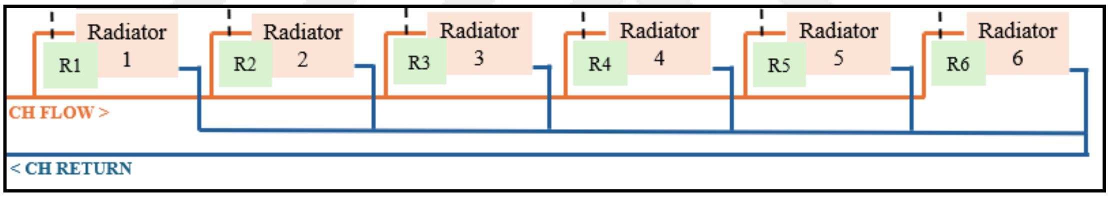


Figure 3.15 System basic schema of radiators and solenoids (Personnel Archive, 2023)

3.7.8 LCD Keypad Shield

The system comprises an LCD Keypad that enables monitoring and manual temperature adjustment of each zone. The hardware component depicted in Figure 3.16 is the LCD Keypad Shield, which combines a 16x2 character LCD screen with a keypad. It offers a user-friendly interface for Arduino-based projects. The shield is intended to be easily stackable on top of an Arduino board, allowing for seamless integration and expanded capabilities.

Figure 3.16 LCD keypad shield (14Core, 2013)

The 16x2 LCD display of the shield offers precise and straightforward visual feedback for your applications. It offers a two-line, 16-character-per-line output, making it ideal for presenting information such as sensor readings, system status, or custom messages. The display employs liquid crystal technology, ensuring low power consumption while maintaining good visibility in various lighting conditions. The shield also includes a built-in keypad, adding an interactive element to the LCD. Figure 3.17 depicts the pins and button features.

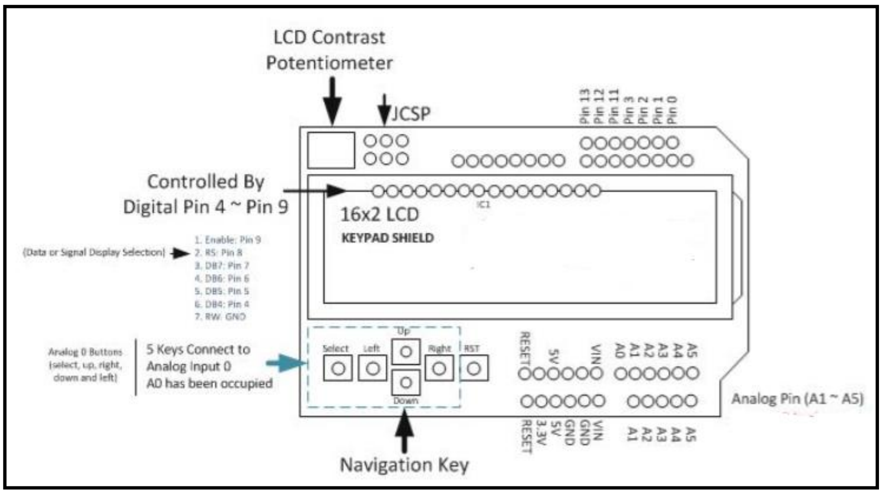


Figure 3.17 Pin function of LCD keypad shield (14Core, 2013)

The keypad typically comprises a grid of push buttons that allow users to input commands, navigate menus, or trigger specific actions in software. Combining an LCD and keypad simplifies the user interface of this thesis.

3.7.9 Multi Outputs Power Module

The 3.3V and 5V Breadboard Power Supply Module is a versatile tool that includes a built-in series diode and polarity reversal protection. It accepts input voltages ranging from 6.5V to 12V and produces reliable outputs of 3.3V and +5V. This module is essential for experimenters engaged in testing and prototyping electronic circuits on breadboards or perforated/Veroboard surfaces. It is important to note that NodeMCU require 3.3V, while PIR sensors operate with 5V. The solenoid valve supplies the incoming 12V to the module depicted in figure 3.18.

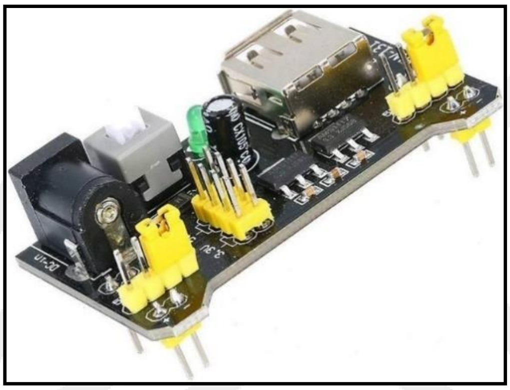


Figure 3.18 Multi outputs power module (Personnel Archive, 2023)

The device has the following features: it supports input voltages of 6.5-12 V (DC) or 5V USB power supply, has switchable output voltages between 3.3V and 5V, and is capable of delivering a maximum output current of less than 700 mA. Additionally, it features an external Input voltage ON/OFF switch for user convenience and enables independent control of upper and lower Breadboard Power Rails, switchable to 0V, 3.3V, or 5V using jumpers on any rail. Equipped with two sets of 3.3V and 5V DC output plug pins onboard, this device facilitates convenient external lead utilization. Additionally, it includes a USB device connector for powering external devices.

3.7.10 Relay Module

The one-way 5V relay module shown in Figure 3.19 is a controllable relay board that allows for the manipulation of its contacts using a 5V power source from the Slave Module or any compatible microcontroller board. It consumes only 20mA of current from the microcontroller when activated. This module is widely used in various domains, including hobbies, industry, and robotics, and is essential for diverse projects.

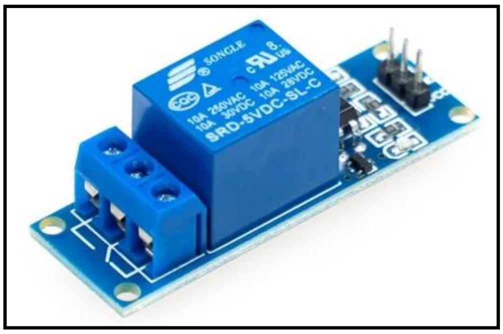


Figure 3.19 Relay module (Teoman, 2023)

The board is capable of relaying currents up to 10A at 30VDC or 220VAC. It features individual control LEDs that correspond to each relay, providing visual feedback. The relays are triggered by logic 0 (0V), making it compatible with microcontroller logic. This equipment is particularly crucial for controlling a solenoid valve due to its propensity to draw high currents and operate at a 12V power supply.

3.8 Heat Radiators

When designing a hot water heating system, radiator selection is typically based on heat loss calculations for the spaces being heated, considering panel efficiencies. Distribution and return pipe diameters are then dimensioned, and the pressure drop at the critical circuit is calculated within acceptable velocity limits based on heat loads. It is important to note that all evaluations are objective and free from bias. Finally, the circulation pump is selected based on the calculated pressure drop to ensure it can pump water into the critical circuit. Basic type is in Figure 3.20.

Figure 3.20 Heat radiator (Baymak, 2023)

Panel radiators are a popular choice for heating spaces due to their elegant appearance and high efficiency. They are designed with connections on each side, making installation easy in any desired space. These radiators are typically made from economical materials such as steel or, for higher efficiency, more expensive aluminum. The number of convectors is the key parameter that influences the type of radiator chosen. Different radiator types are commonly produced with varying heating capacities. These types include PC, PCP, and PCCP, which are based on panel (P) and convector (C) counts. Figure 3.21 illustrates these types.

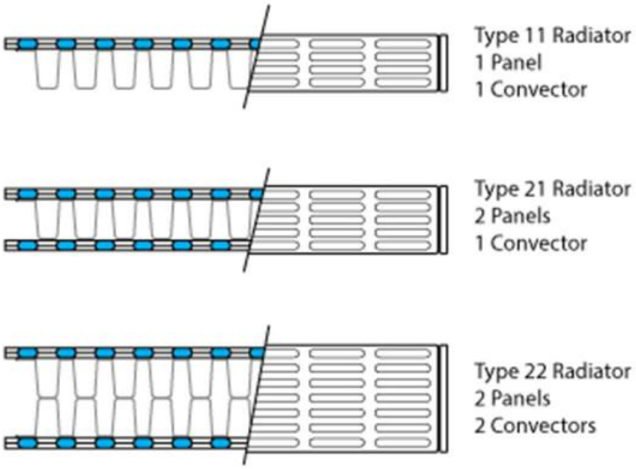


Figure 3.21 Types of heat radiators (Baymak, 2023)

The study was conducted in a house that used Type22 steel Panel-Convector-Convector-Convector-Panel radiators. Each radiator measured 600mm x 1000mm and reached 1421 Watts at an average temperature of 70 ℃, with an AT of 50 ℃, when compared to the home temperature in four areas. The living room radiator measured 600mm x 1400mm and reached 1989 watts, while the bathroom radiator measured 900mm x 400mm and reached 786 watts. Panel radiators transmit circulating water to space through two different heat transfer mechanisms. The radiator transfers heat to the environment primarily through radiation as the water circulating in the radiator moves on the panel surface. Additionally, heating the air within the environment is another way for the transfer of heat through convection. To ensure effective convection and radiation, it is essential to avoid obstructing the front and top surfaces of the radiators by placing objects correctly, whether for decorative or placement purposes (Baymak, 2023). The radiant heating unit is near the structural partition, resulting in direct thermal dissipation from the exterior side to the wall-facing aspect of the heating unit. This study aimed to mitigate the thermal dissipation from the external side of the radiant heating unit. Initially, the heat loss from the heating unit's exterior was computed based on the uninsulated radiator.

3.9 Thermal Isolation of Building

Proper insulation is crucial for regulating a home's temperature and retaining warmth. An effectively insulated house acts as a barrier, minimizing heat transfer between the interior and exterior environments. During colder seasons, insulation helps to trap generated heat inside, preventing it from escaping. This not only ensures a more comfortable living space but also contributes to energy efficiency by reducing the need for excessive heating. Furthermore, a properly insulated home maintains a stable indoor temperature, providing a comfortable living environment while reducing the need for heating systems. As shown in Figure 3.22, the insulation status of homes in Türkiye has a significant impact on heating practices (Teskeredzic et al., 2018).

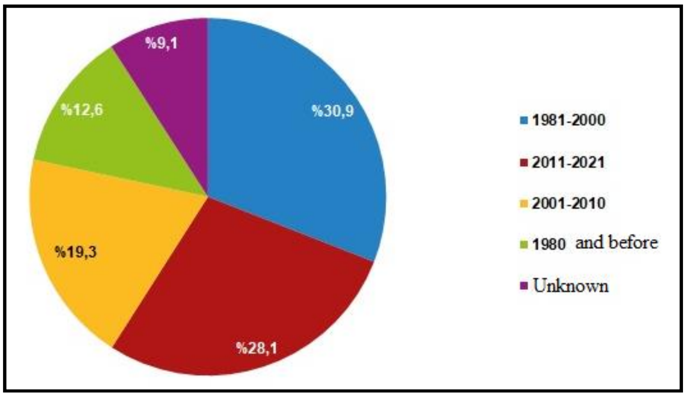


Figure 3.22 The construction year of the occupied building, 2021 in Türkiye (TUIK, 2022)

Turkish households with insulated homes consume less gas for heating compared to those without insulation. As this house was constructed between 1981 and 2000, there were no regulations on thermal insulation for houses built during this period. Therefore, the thermal insulation consists of single brick and lining. The relevant regulation was published in 2008 (Official Gazette, 2008). As a result, over 50% of the houses built before 2008 lack proper insulation (TUIK, 2023).

3.10 Temperature and Humidity Relationship

This study evaluates heat stress using the heat index formulated by Rothfusz in collaboration with the National Weather Service in 1990. The heat index has been widely adopted and has demonstrated its effectiveness in assessing the vulnerability of outdoor laborers to heat-related illnesses, as emphasized by Quandt et al. in 2013. In contrast to other indicators, such as the wet-bulb globe temperature, which is not universally observed due to the absence of the black globe temperature, the heat index, also known as the apparent temperature (AT), can be easily calculated using air temperature (T, °C) and relative humidity (RH, %). The daily apparent temperature is derived from the daily air temperature and relative humidity values using the Rothfusz regression model, which was introduced by Rothfusz in 1990.

The relationship between humidity and perceived temperature is intricate in Equation 3.2. Variations in relative humidity can significantly impact how individuals perceive and respond to temperature. High humidity levels impede the body's natural cooling mechanism through evaporation, making individuals feel hotter than the actual air temperature. Conversely, low humidity levels can contribute to a more comfortable perception of temperature. Therefore, it is essential to comprehend the relationship between humidity and perceived temperature to accurately evaluate heat stress and implement effective measures for heat-related safety, especially for outdoor workers who face varying climatic conditions. The formula for calculating the AT is as follows:

$$
\begin{aligned}
AT = -8.7847 + 1.6114 * T - 0.012308 * \mathrm{T2} + \\
(2.3385 - 0.14612 * \mathrm{T} + 0.022117 * \mathrm{T2}) * \mathrm{RH} + \\
(-0.016425 + 0.0072546 * \mathrm{T} - 0{,}00003582 * \mathrm{T2}) * \mathrm{RH2}
\end{aligned}
\tag{3.2}
$$

3.11 Gas-Fired Combi Boiler

Gas-fired combi boilers are heating units that are versatile and designed for both space heating and domestic hot water production. They can be controlled using various methods, including on/off control proprietary software provided by manufacturers and open-source solutions like OpenTherm. The control mechanisms play a crucial role in regulating the operation of essential components within the boiler system. A gas combi boiler comprises several key components, including a circulation pump, fan, temperature sensors, three-way valve, expansion tank, safety devices such as safety thermistors, and a pressure relief valve. These elements collectively contribute to the functionality and safety of the heating system (Teoman et al., 2022). Although examining the intricacies of connections may not be particularly useful for thesis study, we can observe the sub-piping connections specific to the combi boiler, where the tests will be conducted, in Figure 3.23.

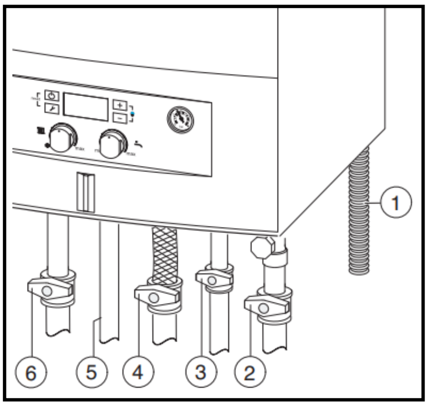


Figure 3.23 Bosch Condens 2000 W plumbing fittings (Bosch, 2017)

- Drain hose (1)
- Radiator circuit return valve (2)
- Cold water inlet valve (3)
- Gas inlet valve (4)
- Hot water outlet (5)
- Radiator circuit flow valve (6)

The circulation pump is illustrated in Figure 3.24 which ensures the efficient distribution of hot water throughout the heating system, while the fan facilitates the combustion process, promoting optimal energy utilization.

Figure 3.24 WILO RKC circulation pump (Personnel Archive, 2023)

The discharge head of the pump is determined by the total water flow rate passing through it per hour. It is important to select the correct head to ensure optimal performance.

The three-way valve directs the flow of hot water between the space heating and domestic hot water circuits, ensuring a seamless transition between the two functions. Combi boilers must be set to supply either the DHW or CH circuit, but not both. An expansion vessel, such as the one shown in Figure 3.25, accommodates the expansion and contraction of water as it heats and cools, thereby maintaining system pressure. The diagram below can help determine whether the integrated expansion tank is sufficient or if an additional expansion tank is required (not intended for underfloor heating).

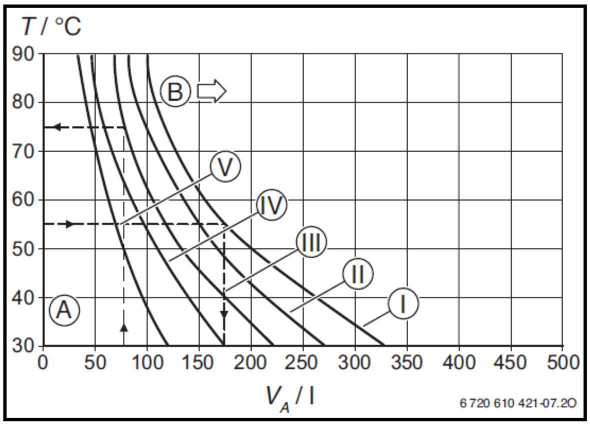


Figure 3.25 Expansion vessel working range (Bosch, 2017)

- Initial pressure 0.2 bar (I)
- Initial pressure 0.5 bar (II)
- Initial pressure 0.75 bar (III)
- Initial pressure 1.0 bar (IV)
- Initial pressure 1.2 bar (V)
- Total volume of the system (Liters) (V_A)
- Expansion tank operating range (A)
- A larger expansion tank is needed in this range (B)

The preliminary water volume of the expansion tank should be either 1% of the system water volume or 20% of the nominal volume of the expansion tank. For instance, if the system water volume is 160 liters, the expansion tank should be 8 liters (1% = 1.6 liters, 20% = 32 liters). The safety valve's operating differential is set at 0.5 bar in compliance with standards. The expansion tank's initial pressure should be equal to the static height of the system above the heat exchanger. The maximum operating pressure is set at 3 bar. Figure 3.25 provides a general perspective on whether the existing expansion tank is adequate or if an additional one is needed in the decision-making process according to DIN EN 12828.

Gas-fired combi boilers include a fan, which is illustrated in Figure 3.29 as a critical component in their heating systems. The fan plays a crucial role in the combustion process, ensuring the proper mixing of air and natural gas before ignition. The fan contributes to the efficient and controlled burning of fuel within the boiler by facilitating the combustion air supply.

Figure 3.26 Bosch Condens 2000 W fan (Personnel Archive, 2023)

The fan works together with other components, including the burner, to produce a stable and controlled flame. This controlled combustion process is crucial for maximizing energy efficiency and minimizing emissions. Furthermore, the fan assists in regulating the air-fuel mixture, promoting safe and dependable operation.

Temperature sensors continuously monitor temperature levels, providing valuable input for control algorithms. The flow detecting temperature sensor is a crucial component in a boiler as it measures the temperature of the heated water at the first outlet of the heat exchanger. The DHW sensor is also critical as it is continuously used when washing with hot water or rinsing hands in the kitchen. It is especially important to consider that many worldwide standards set a critical limit of 60°C, above which human skin can scald. The system operates more efficiently with a colder gas outlet, as it uses the heat from the hot exhaust gas during condensation to heat the return water.

Figure 3.27 illustrates the gas valve, which is where the gas line first connects to the boiler in the user's home. The valve allows observation of the inlet pressure entering the house, which should be 21mBar for Türkiye. The valve is compatible with both natural gas and LPG. Gas valves that operate with Direct Current allow gas to pass to the burner through the built-in solenoid structure. The gas valve is a crucial component in modulating the device for energy efficiency.

Figure 3.27 Gas valve SIT Sigma 845 (SIT Group, 2017)

The output ranges of the gas valve are ensured through voltage and current balance, providing a wider control field. However, the range used for the Bosch Condens 2000 W combi is narrower. When the boiler self-starts at the lowest capacity, the outlet pressure which is defined by gas valve drops to around 1.5mBar. When operating at maximum capacity, the outlet pressure is approximately 9mBar.

There are some safety components are illustrated in Figure 3.28 which are in combi boiler. Pressure switch is responsible for checking closed-loop piping pressure and the pressure relief valve, function as fail-safes to prevent overheating and excessive pressure within the system, enhancing overall reliability and user safety.

Relief Valve 3 Bar   Pressure Switch 0.5 Bar   Overheat Thermostat 105° C

Figure 3.28 Safety components of combi boiler (Personnel Archive, 2023)

In summary, gas combi boilers are advanced heating solutions with sophisticated control systems that integrate a range of components to deliver efficient and reliable space heating and hot water production. The diverse control methods and safety features contribute to the adaptability and performance of these systems in residential heating applications. The device detects demand for hot water usage and activates the heating process by transitioning to the DHW mode after receiving a demand, typically at a rate of 2.5 liters per minute or higher. It includes a paddlewheel that counts rotations magnetically. Figure 3.29 shows that the OpenTherm port is labeled as 'TH' on the connector.

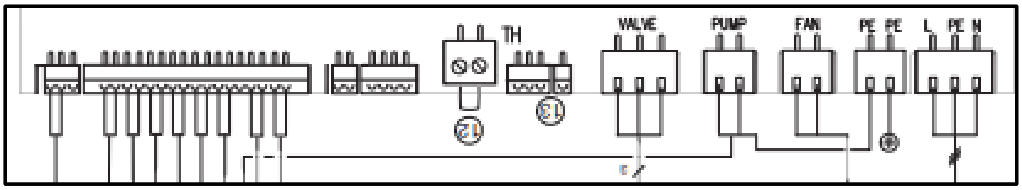


Figure 3.29 A part of electrical schema of Bosch Condens 2000 W (Bosch, 2017)

CHAPTER FOUR

EXPERIMENTAL

Thesis study is designed as a smart heating of a home automation system which is illustrated in Figure 4.1. The system consists of an NodeMCU as the first-level node and a series of NodeMCU (M1, M2, M3, M4, M5 and M6) as second-level nodes. Each NodeMCU represents a specific zone and collects environmental data (temperature, humidity, motion) through various sensors. The Master NodeMCU analyzes this data and based on predefined conditions, performs boiler control, and manages relays.

The Slave NodeMCU use Wi-Fi to continuously send temperature, humidity, and motion data to the master NodeMCU using the MQTT protocol. These data are transmitted to the master NodeMCU through Hive MQTT broker. Hive HQ was used as the MQTT broker. The broker can be accessed by up to one hundred devices simultaneously for free. The master NodeMCU analyzes the received data and checks conditions for a specific zone. For example, if the temperature is above 21°C, humidity is below 60%, and motion is detected, the master NodeMCU activates the relay. The relay can be used to control solenoid valves of interested in the respective zone.

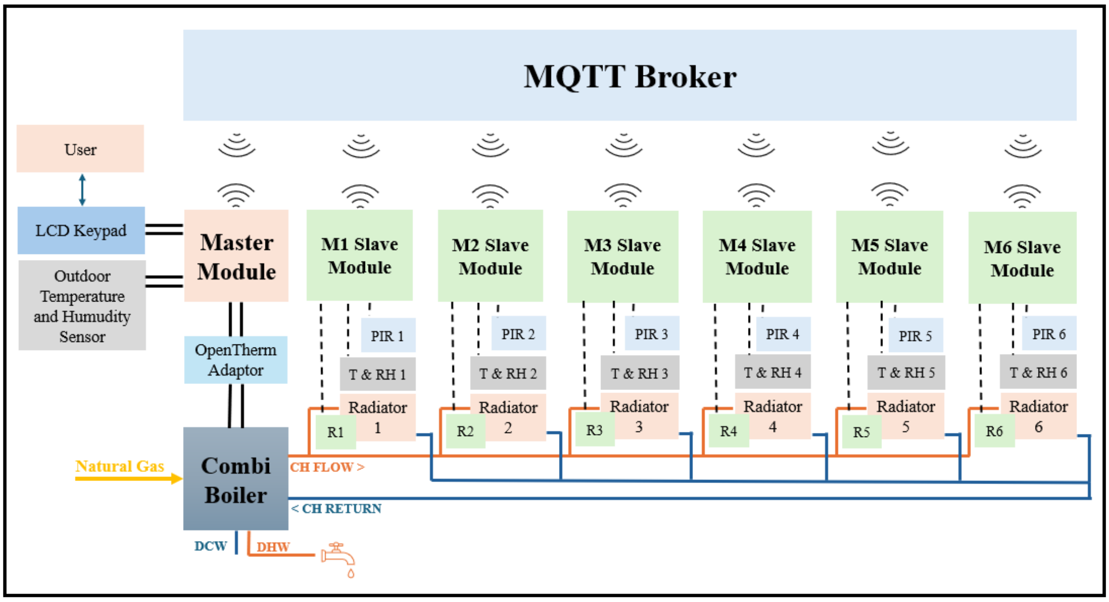


Figure 4.1 The schematic of all system (Personnel Archive, 2023)

The master NodeMCU also controls a boiler using the OpenTherm library, providing overall heating and cooling control for the system. By analyzing temperature, humidity, and motion data, the master NodeMCU adjusts the boiler set temperature. This way, a smart heating and control system is achieved with individual conditions met for each zone.

As previously stated in section 3.7.4, the OpenTherm protocol must be utilized to establish a connection with boilers. A library has been created for the code released by the OpenTherm organization, which is useful for the Arduino and similar developer communities. However, it is important to note that adherence to specific rules outlined by the organization is also required.

Weather compensation controllers primarily rely on the heat curve to establish the appropriate flow temperature based on the outdoor temperature. When configuring parameters in the controller, modifications to the heat curve and its slope may be necessary. It was mentioned earlier that the OpenTherm protocol should be used to connect to the combi boilers. For the NodeMCU supported by Arduino and similar developer communities, a library has been created for the code released by the OpenTherm organization. However, it is important to note that we also need to adhere to some specific rules outlined by the organization. These rules are explained below.

4.1 The Software and Schematic of Master Device

The code initializes the MQTT client to communicate with the broker and subscribes to MQTT topics to receive sensor data from M1, M2, M3, M4, M5, and M6. The callback function defines actions when MQTT messages are received. Figure 4.2 shows the schematic for the master device side.

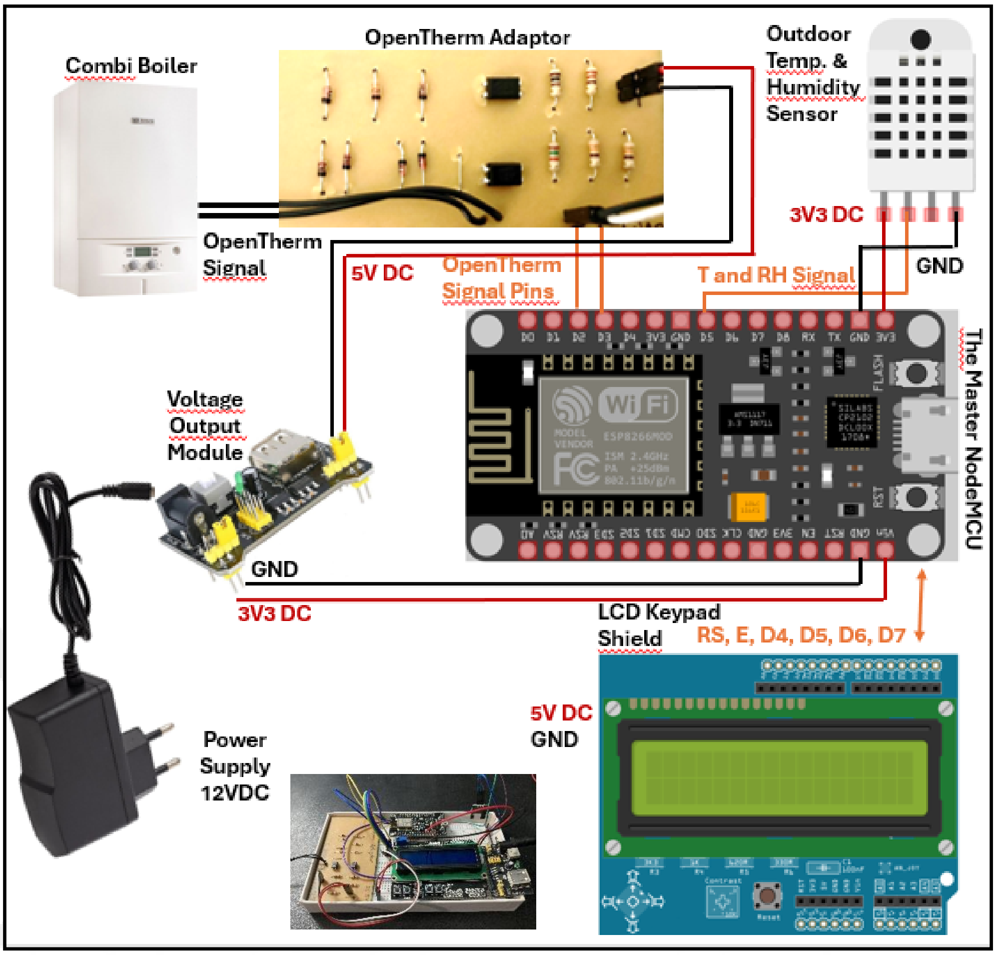
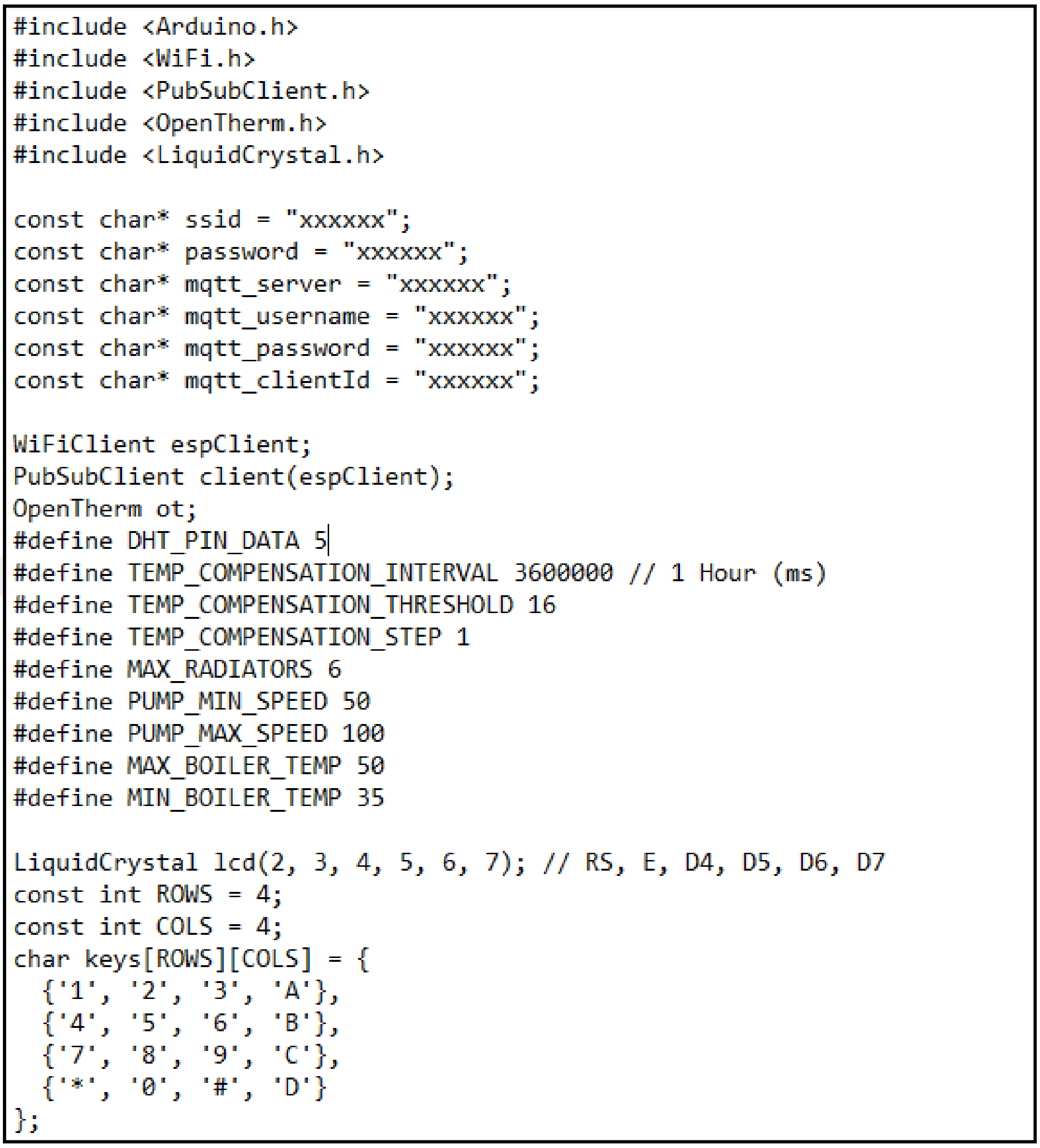


Figure 4.2 Schematic of the master device side (Personnel Archive, 2023)

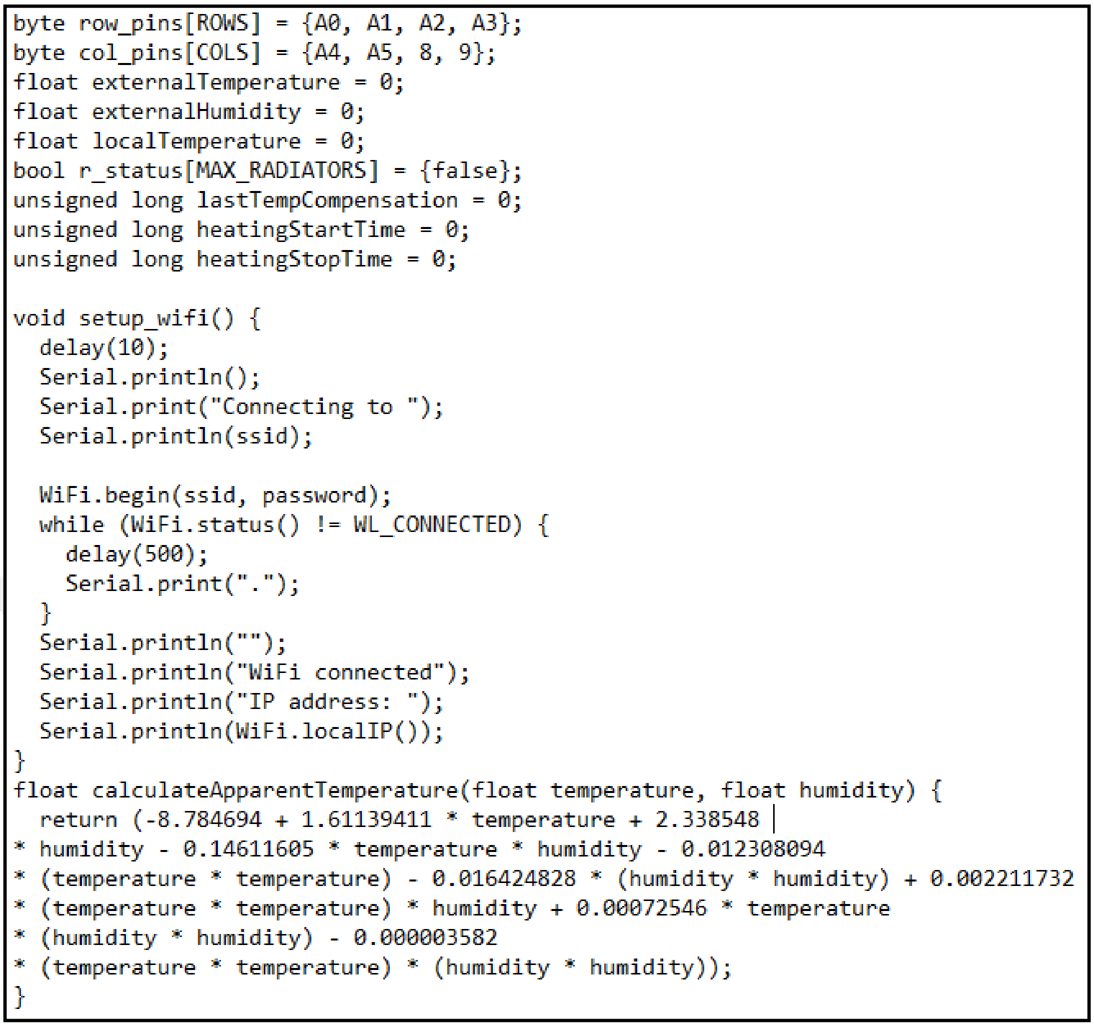
The setup function initializes serial communication, sets up the MQTT server, and configures subscriptions. The loop function continuously checks for MQTT messages and performs sensor data analysis, OpenTherm boiler control, and other tasks. The reconnect function aims to re-establish a connection with the MQTT broker in case of disconnection. Figure 4.3 illustrates the process of including five different libraries in the software, setting up the Wi-Fi connection with SSID and password, and defining the parameters of the broker server. The 'PubSubClient.h' library facilitates the MQTT protocol with various specialized commands. Additionally, the OpenTherm protocol is utilized, with an object named 'ot' created for this purpose. The system is designed to compensate for temperature fluctuations every hour. The pump speed adjusts based on the number of active radiators to ensure optimal heating efficiency. Additionally, the system sets the maximum boiler temperature to 50 ℃ and the minimum to 35 ℃. To facilitate user input for both automatic and manual control, the system includes an LCD keypad connection.



```
#include <Arduino.h>
#include <WiFi.h>
#include <PubSubClient.h>
#include <OpenTherm.h>
#include <LiquidCrystal.h>

const char* ssid = "xxxxxx";
const char* password = "xxxxxx";
const char* mqtt_server = "xxxxxx";
const char* mqtt_username = "xxxxxx";
const char* mqtt_password = "xxxxxx";
const char* mqtt_clientId = "xxxxxx";

WiFiClient espClient;
PubSubClient client(espClient);
OpenTherm ot;
#define DHT_PIN_DATA 5
#define TEMP_COMPENSATION_INTERVAL 3600000 // 1 Hour (ms)
#define TEMP_COMPENSATION_THRESHOLD 16
#define TEMP_COMPENSATION_STEP 1
#define MAX_RADIATORS 6
#define PUMP_MIN_SPEED 50
#define PUMP_MAX_SPEED 100
#define MAX_BOILER_TEMP 50
#define MIN_BOILER_TEMP 35

LiquidCrystal lcd(2, 3, 4, 5, 6, 7); // RS, E, D4, D5, D6, D7
const int ROWS = 4;
const int COLS = 4;
char keys[ROWS][COLS] = {
  {'1', '2', '3', 'A'},
  {'4', '5', '6', 'B'},
  {'7', '8', '9', 'C'},
  {'*', '0', '#', 'D'}
};
```

Figure 4.3 The master device software - part one (Personnel Archive, 2023)

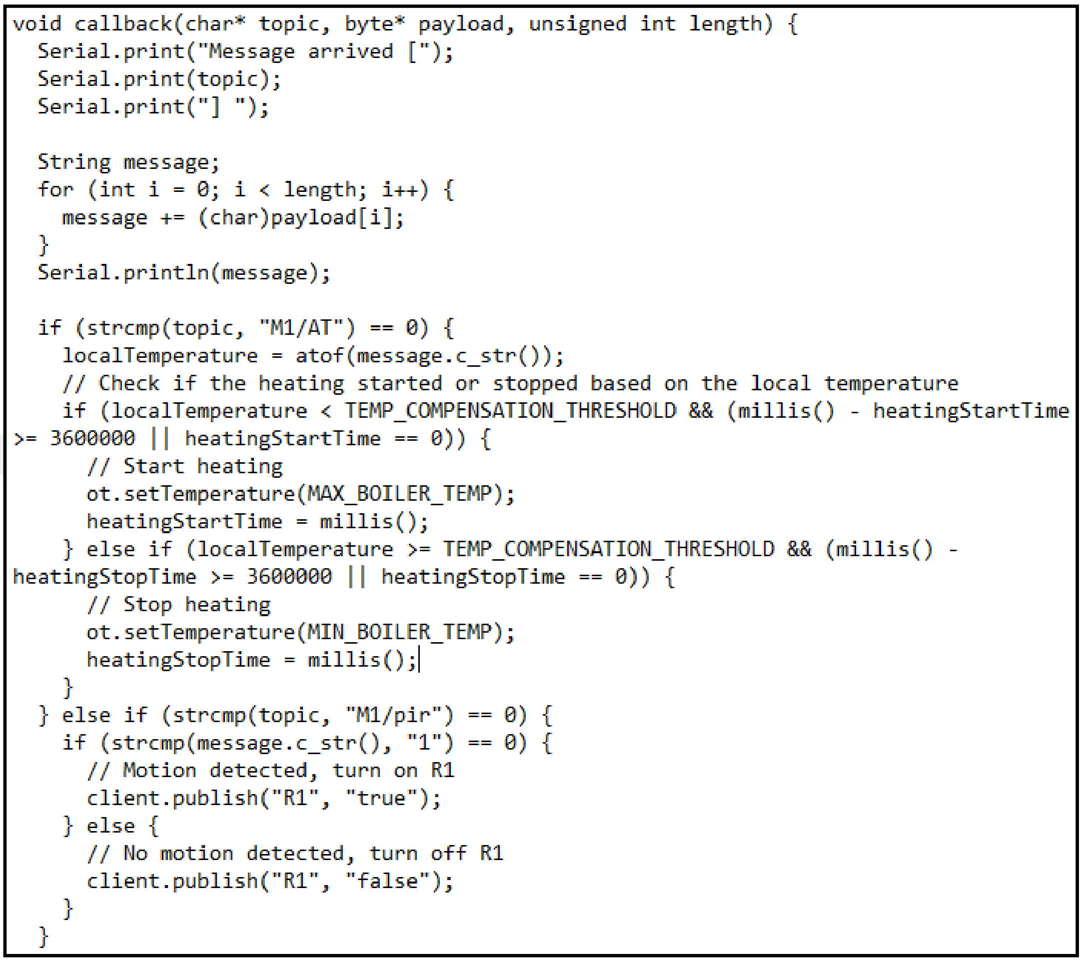
Figure 4.4 provides a code snippet that sets up a Wi-Fi connection and calculates the apparent temperature based on environmental data. It defines pin assignments for a keypad matrix and initializes variables to store temperature, humidity, and system timestamps. The function ‘setup_wifi’ is responsible for establishing the Wi-Fi connection, while ‘calculateApparentTemperature’ computes the apparent temperature using a mathematical formula. These functionalities are essential for IoT devices to efficiently connect to networks and process environmental data.



```
byte row_pins[ROWS] = {A0, A1, A2, A3};
byte col_pins[COLS] = {A4, A5, 8, 9};
float externalTemperature = 0;
float externalHumidity = 0;
float localTemperature = 0;
bool r_status[MAX_RADIATORS] = {false};
unsigned long lastTempCompensation = 0;
unsigned long heatingStartTime = 0;
unsigned long heatingStopTime = 0;

void setup_wifi() {
  delay(10);
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
}
float calculateApparentTemperature(float temperature, float humidity) {
  return (-8.784694 + 1.61139411 * temperature + 2.338548
* humidity - 0.14611605 * temperature * humidity - 0.012308094
* (temperature * temperature) - 0.016424828 * (humidity * humidity) + 0.002211732
* (temperature * temperature) * humidity + 0.00072546 * temperature
* (humidity * humidity) - 0.000003582
* (temperature * temperature) * (humidity * humidity));
}
```

Figure 4.4 The master device software - part two (Personnel Archive, 2023)

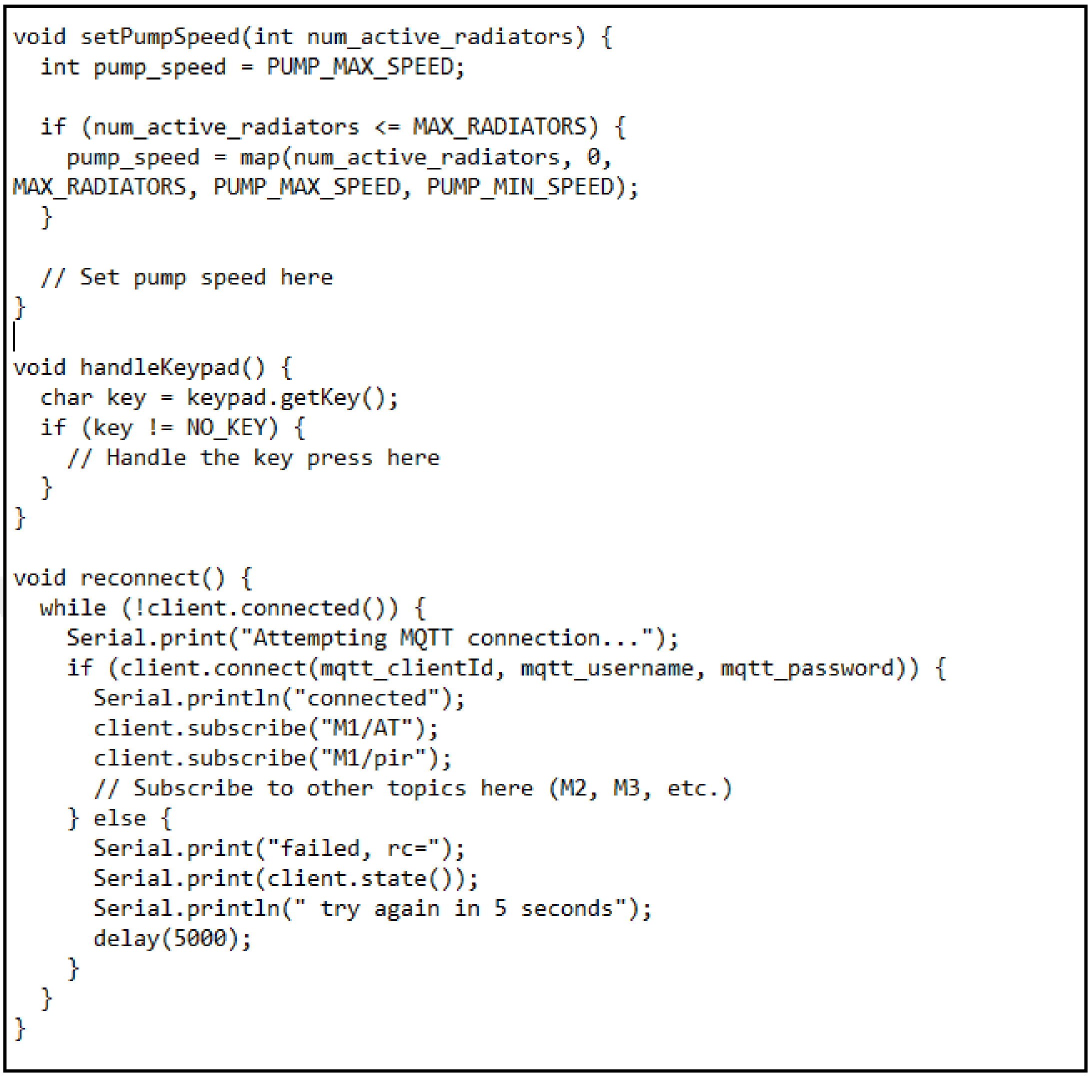
Figure 4.5 shows The MQTT message handling system in the IoT device includes the essential component of a callback function. This function is automatically triggered by the MQTT client library when a message is received on a subscribed topic. It then processes the payload of the message by converting the byte array into a string representation. This string is printed to the serial monitor for debugging purposes. The function then analyzes the topic of the received message to determine the appropriate action. If the message pertains to ambient temperature ("M1/AT"), the function extracts the local temperature from the payload and evaluates certain conditions, such as elapsed time since the last heating operation. Based on these conditions, it adjusts the boiler temperature to regulate the heating system. If the message pertains to a passive infrared motion sensor (M1/pir), the function analyzes the payload to detect motion. It can trig an action by publishing a message to activate R1. If no motion is detected and suitable for algorithm, it publishes a message to deactivate the relay, thereby turning off the corresponding device.



```
void callback(char* topic, byte* payload, unsigned int length) {
  Serial.print("Message arrived [");
  Serial.print(topic);
  Serial.print("] ");

  String message;
  for (int i = 0; i < length; i++) {
    message += (char)payload[i];
  }
  Serial.println(message);

  if (strcmp(topic, "M1/AT") == 0) {
    localTemperature = atof(message.c_str());
    // Check if the heating started or stopped based on the local temperature
    if (localTemperature < TEMP_COMPENSATION_THRESHOLD && (millis() - heatingStartTime
>= 3600000 || heatingStartTime == 0)) {
      // Start heating
      ot.setTemperature(MAX_BOILER_TEMP);
      heatingStartTime = millis();
    } else if (localTemperature >= TEMP_COMPENSATION_THRESHOLD && (millis() -
heatingStopTime >= 3600000 || heatingStopTime == 0)) {
      // Stop heating
      ot.setTemperature(MIN_BOILER_TEMP);
      heatingStopTime = millis();
    }
  } else if (strcmp(topic, "M1/pir") == 0) {
    if (strcmp(message.c_str(), "1") == 0) {
      // Motion detected, turn on R1
      client.publish("R1", "true");
    } else {
      // No motion detected, turn off R1
      client.publish("R1", "false");
    }
  }
```

Figure 4.5 The master device software - part three (Personnel Archive, 2023)

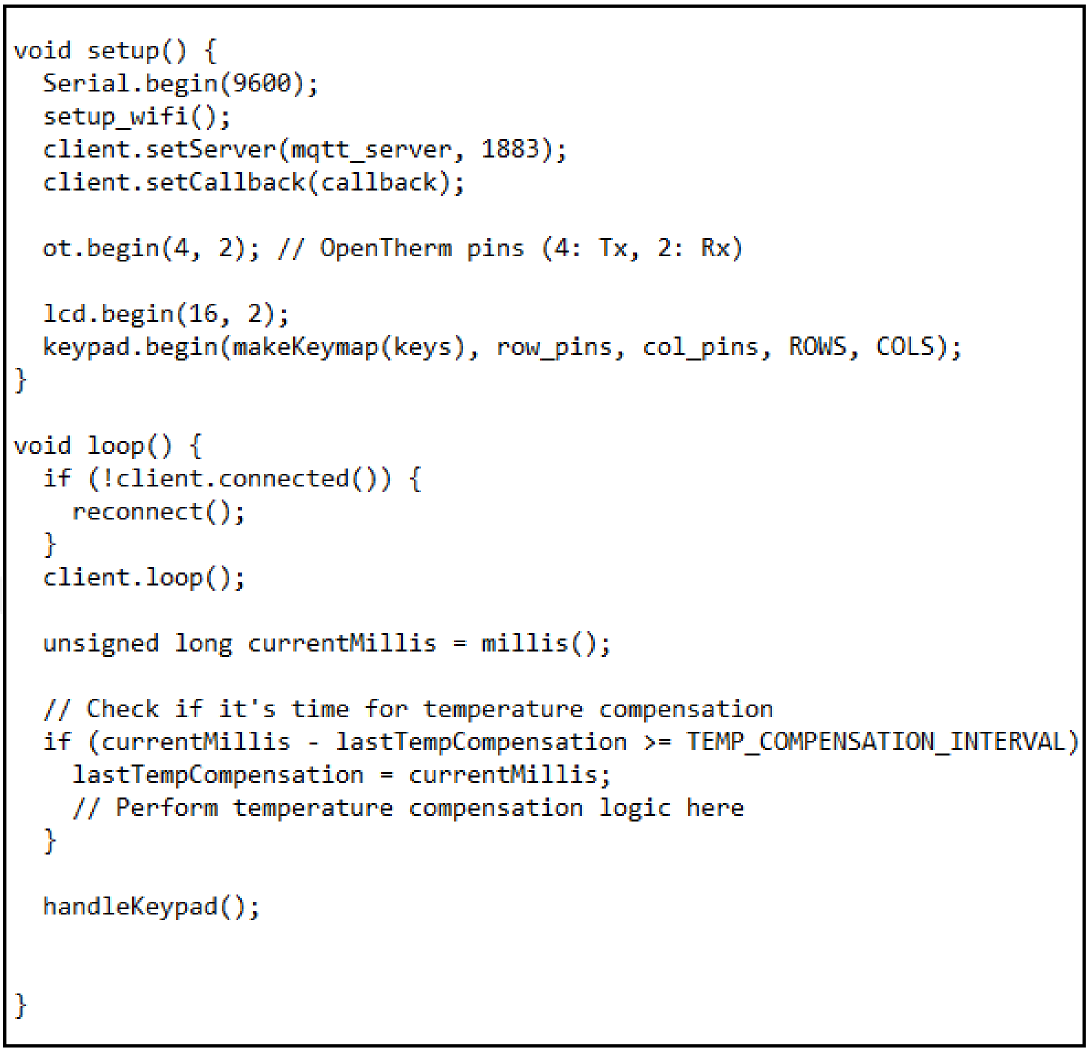
Figure 4.6 defines the OpenTherm pins from NodeMCU to the OpenTherm Adaptor, which connects to the gas-fired combi boiler. The diagram also displays the current temperature data. The LCD keypad is used for temperature compensation to control the combi boiler. The 'handleKeypad' function processes keypad inputs to enable user interaction. The pump speed is set according to the active radiators. This section also defines the process for reconnecting to Wi-Fi. The 'setPumpSpeed' function adjusts the pump speed based on the number of active radiators in a heating system to ensure efficient heating operation. It calculates the pump speed according to the number of active radiators and dynamically adjusts the pump speed using the 'map' function to map the range of active radiators to the range of pump speeds, if the number of active radiators is within the specified range.



```
void setPumpSpeed(int num_active_radiators) {
  int pump_speed = PUMP_MAX_SPEED;

  if (num_active_radiators <= MAX_RADIATORS) {
    pump_speed = map(num_active_radiators, 0,
MAX_RADIATORS, PUMP_MAX_SPEED, PUMP_MIN_SPEED);
  }

  // Set pump speed here
}

void handleKeypad() {
  char key = keypad.getKey();
  if (key != NO_KEY) {
    // Handle the key press here
  }
}

void reconnect() {
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    if (client.connect(mqtt_clientId, mqtt_username, mqtt_password)) {
      Serial.println("connected");
      client.subscribe("M1/AT");
      client.subscribe("M1/pir");
      // Subscribe to other topics here (M2, M3, etc.)
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 5 seconds");
      delay(5000);
    }
  }
}
```

Figure 4.6 The master device software - part four (Personnel Archive, 2023)

In Figure 4.7, the function ‘setup’ initializes the device by configuring the MQTT server and port, establishing a Wi-Fi connection, setting up serial communication, initializing OpenTherm pins for communication, and setting up an LCD display and keypad for user interaction. In the function ‘loop’ it checks for a connection to the MQTT broker and attempts to reconnect if one is not established. The code maintains the MQTT client connection and checks if it is time for temperature compensation based on the elapsed time since the last compensation. If it is time, the temperature compensation logic is executed. Furthermore, the ‘handleKeypad’ function is called to manage any keypad inputs for user interaction.



```
void setup() {
  Serial.begin(9600);
  setup_wifi();
  client.setServer(mqtt_server, 1883);
  client.setCallback(callback);

  ot.begin(4, 2); // OpenTherm pins (4: Tx, 2: Rx)

  lcd.begin(16, 2);
  keypad.begin(makeKeymap(keys), row_pins, col_pins, ROWS, COLS);
}

void loop() {
  if (!client.connected()) {
    reconnect();
  }
  client.loop();

  unsigned long currentMillis = millis();

  // Check if it's time for temperature compensation
  if (currentMillis - lastTempCompensation >= TEMP_COMPENSATION_INTERVAL)
    lastTempCompensation = currentMillis;
    // Perform temperature compensation logic here
  }

  handleKeypad();


}
```

Figure 4.7 The master device software - part five (Personnel Archive, 2023)

4.2 The Software and Schematic of Slave Devices

The slave devices in Figure 4.8 range from M1 to M6 and share the same software, except for the module and solenoid number. The voltage output module provides both 3V3 and 5V to power various circuit components. The solenoid valve is also powered by the voltage output module, which is connected to a 12V power supply output. The temperature and humidity sensor and NodeMCU are powered by the 3V3 source, while the PIR sensor is powered by the 5V source. To prevent damage to the NodeMCU output, a relay is used to drive the solenoid valve.

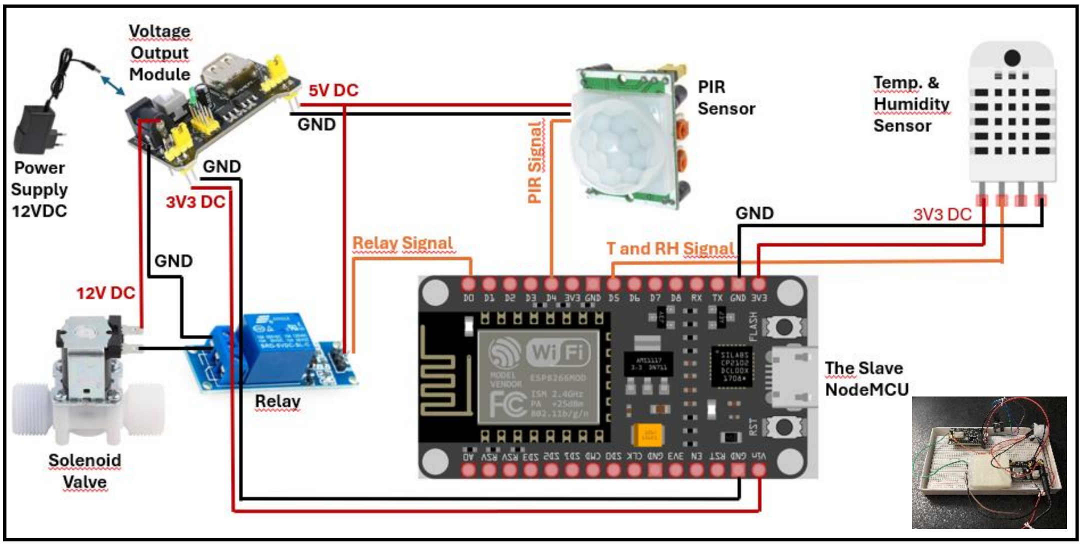
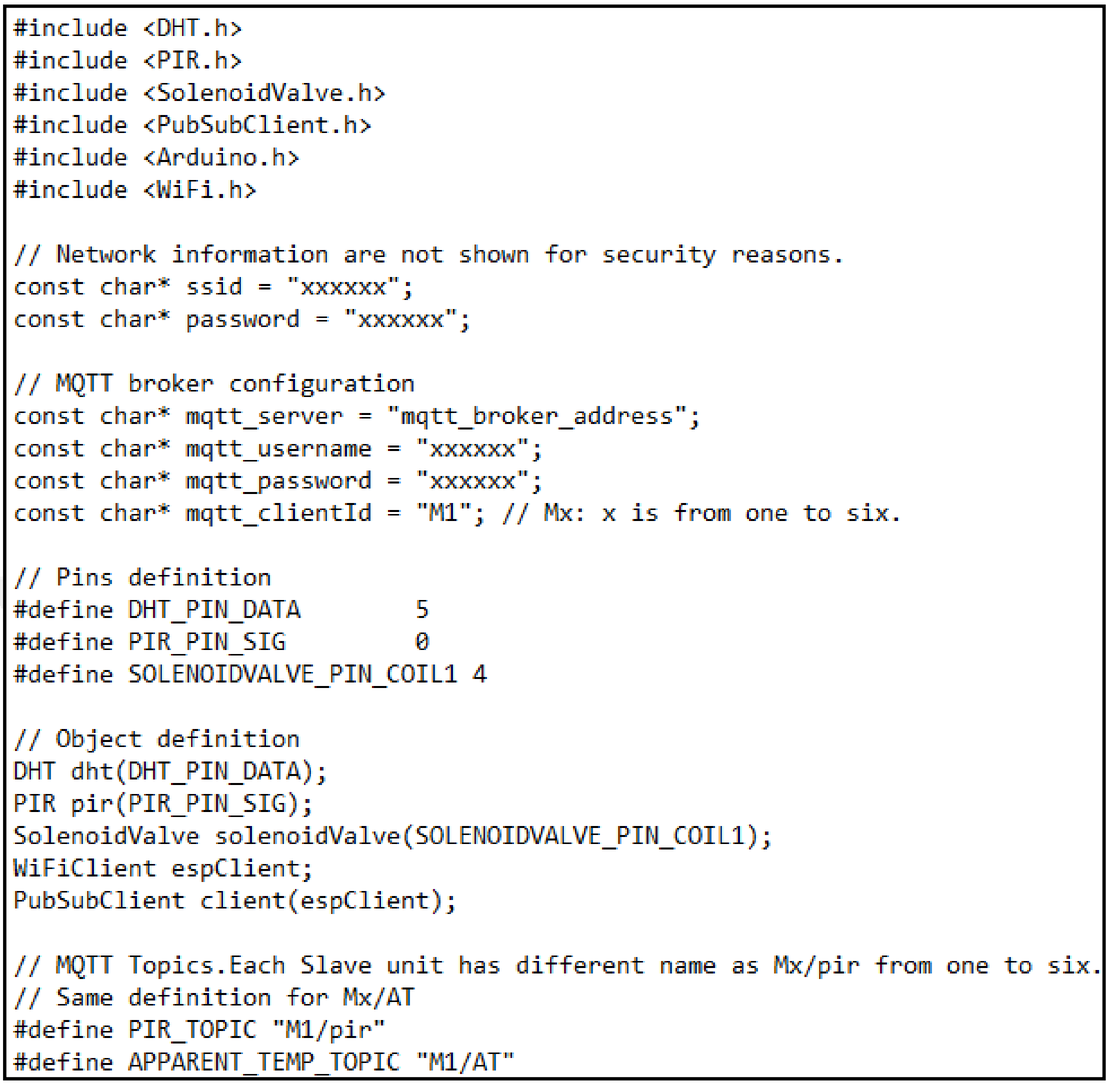


Figure 4.8 Schematic of the slave device side (Personnel Archive, 2023)

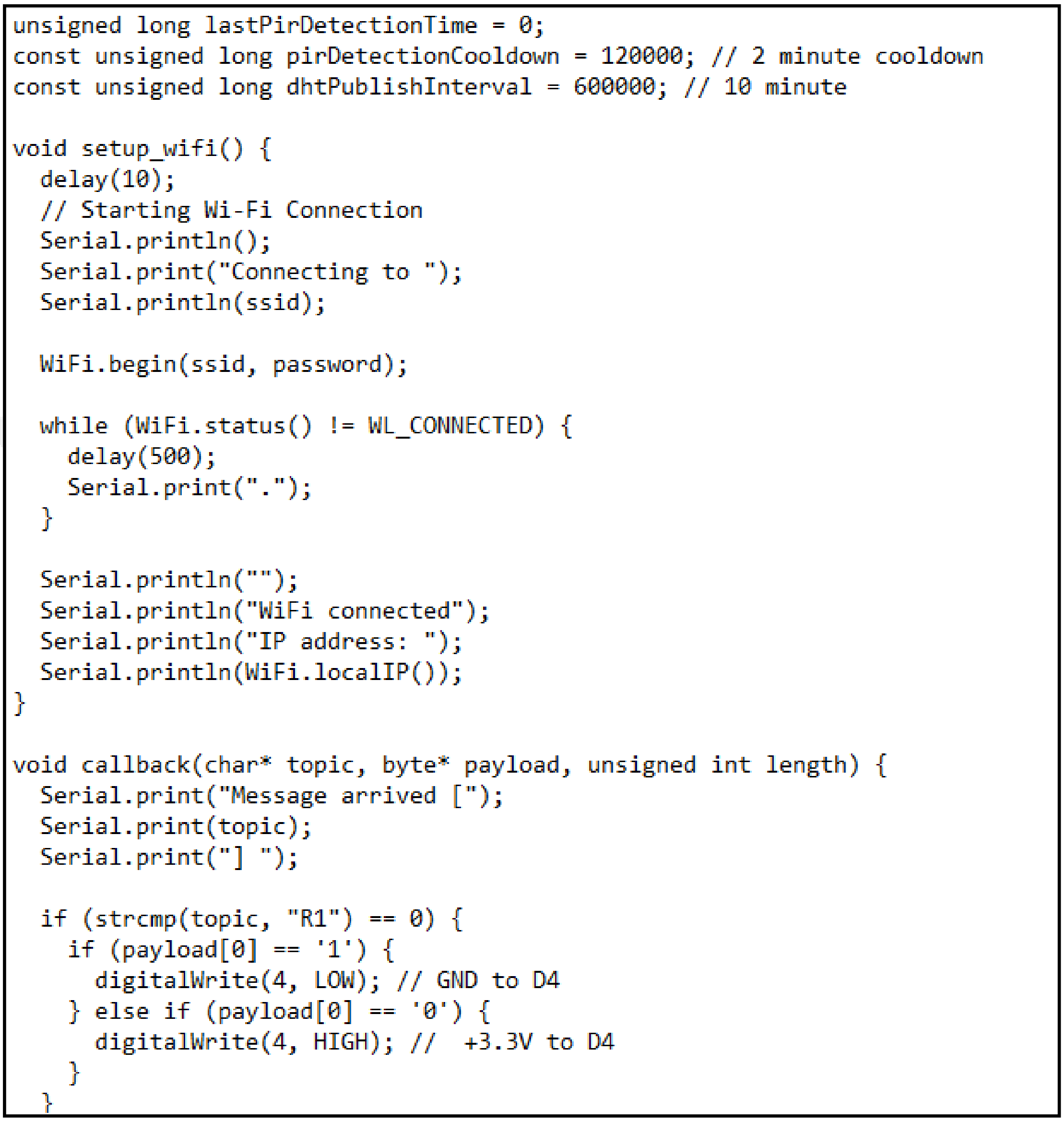
In Figure 4.9, the code provided is for an IoT device that monitors environmental conditions and responds to motion detection. It includes libraries for various components, such as the DHT sensor for temperature and humidity sensing, a PIR sensor for motion detection, and a Solenoid Valve for controlling a valve. Additionally, it utilizes the ‘PubSubClient’ library for MQTT communication, enabling it to publish data to an MQTT broker. For security reasons, the network credentials for connecting to a Wi-Fi network and the MQTT broker configuration details are defined but not shown. Pin definitions are specified for connecting the sensors and actuators to the NodeMCU board. Objects are instantiated for each component, facilitating their interaction within the code. MQTT topics are defined for transmitting data related to PIR detection and apparent temperature, with the client ID 'M1' serving as a prefix for topic identification. This modular structure enables the system to scale by accommodating multiple units differentiated by their respective client IDs. The code forms the foundation for a versatile IoT device capable of monitoring environmental parameters and reacting to motion events while leveraging MQTT for seamless communication with other devices or systems.



```
#include <DHT.h>
#include <PIR.h>
#include <SolenoidValve.h>
#include <PubSubClient.h>
#include <Arduino.h>
#include <WiFi.h>

// Network information are not shown for security reasons.
const char* ssid = "xxxxxx";
const char* password = "xxxxxx";

// MQTT broker configuration
const char* mqtt_server = "mqtt_broker_address";
const char* mqtt_username = "xxxxxx";
const char* mqtt_password = "xxxxxx";
const char* mqtt_clientId = "M1"; // Mx: x is from one to six.

// Pins definition
#define DHT_PIN_DATA        5
#define PIR_PIN_SIG         0
#define SOLENOIDVALVE_PIN_COIL1 4

// Object definition
DHT dht(DHT_PIN_DATA);
PIR pir(PIR_PIN_SIG);
SolenoidValve solenoidValve(SOLENOIDVALVE_PIN_COIL1);
WiFiClient espClient;
PubSubClient client(espClient);

// MQTT Topics.Each Slave unit has different name as Mx/pir from one to six.
// Same definition for Mx/AT
#define PIR_TOPIC "M1/pir"
#define APPARENT_TEMP_TOPIC "M1/AT"
```

Figure 4.9 The software of slave devices – part one (Personnel Archive, 2023)

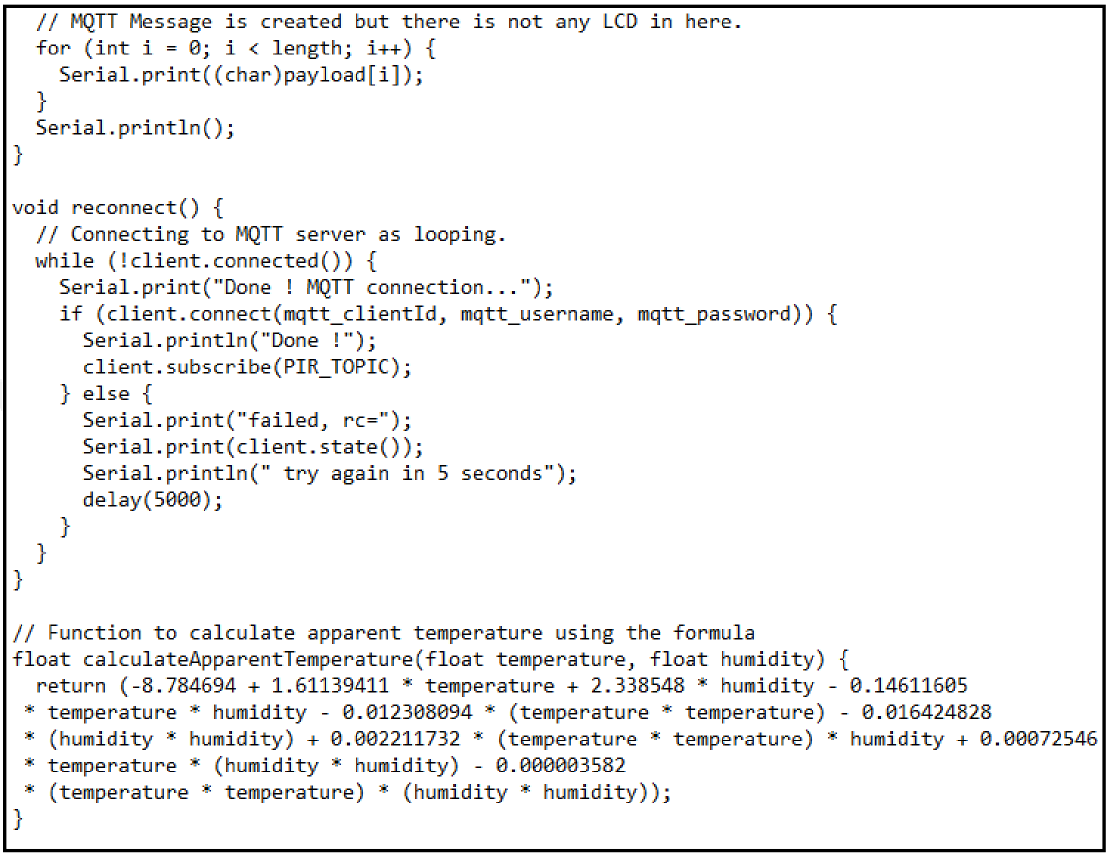
In Figure 4.10 initializes important variables and constants for managing PIR sensor detection and publishing DHT sensor data. The 'lastPirDetectionTime' stores the timestamp of the last PIR detection event, enabling a cooldown period of 2 minutes 'pirDetectionCooldown' between successive detections. The variable ‘dhtPublishInterval’ sets the interval for publishing DHT sensor data to 10 minutes. The 'setup_wifi' function manages the Wi-Fi connection process, attempting to connect to the specified network and displaying the assigned IP address upon successful connection. In addition, the 'callback' function is invoked when MQTT messages are received and processed based on the topic. In this code snippet, messages with the topic 'R1' toggle the state of pin D4 between HIGH and LOW based on the payload content. This setup enables seamless integration with MQTT communication and efficient management of sensor data and network connectivity in IoT devices.



```
unsigned long lastPirDetectionTime = 0;
const unsigned long pirDetectionCooldown = 120000; // 2 minute cooldown
const unsigned long dhtPublishInterval = 600000; // 10 minute

void setup_wifi() {
  delay(10);
  // Starting Wi-Fi Connection
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
}

void callback(char* topic, byte* payload, unsigned int length) {
  Serial.print("Message arrived [");
  Serial.print(topic);
  Serial.print("] ");

  if (strcmp(topic, "R1") == 0) {
    if (payload[0] == '1') {
      digitalWrite(4, LOW); // GND to D4
    } else if (payload[0] == '0') {
      digitalWrite(4, HIGH); //  +3.3V to D4
    }
  }
```

Figure 4.10 The software of slave devices – part two (Personnel Archive, 2023)

Figure 4.11 shows that after processing the MQTT message payload by printing it to the serial monitor, the 'reconnect' function manages the reconnection process to the MQTT server. It continuously attempts to reconnect until a successful connection is established. Upon connection, it subscribes to the PIR topic to receive PIR sensor data. Furthermore, the 'calculateApparentTemperature' function is defined to calculate the apparent temperature using a specific formula based on temperature and humidity readings. This function calculates the apparent temperature based on the input parameters of temperature and humidity. It enhances the device's capabilities by enabling continuous communication with the MQTT server and providing a valuable mechanism for environmental monitoring applications.



```
  // MQTT Message is created but there is not any LCD in here.
  for (int i = 0; i < length; i++) {
    Serial.print((char)payload[i]);
  }
  Serial.println();
}

void reconnect() {
  // Connecting to MQTT server as looping.
  while (!client.connected()) {
    Serial.print("Done ! MQTT connection...");
    if (client.connect(mqtt_clientId, mqtt_username, mqtt_password)) {
      Serial.println("Done !");
      client.subscribe(PIR_TOPIC);
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 5 seconds");
      delay(5000);
    }
  }
}

// Function to calculate apparent temperature using the formula
float calculateApparentTemperature(float temperature, float humidity) {
  return (-8.784694 + 1.61139411 * temperature + 2.338548 * humidity - 0.14611605
 * temperature * humidity - 0.012308094 * (temperature * temperature) - 0.016424828
 * (humidity * humidity) + 0.002211732 * (temperature * temperature) * humidity + 0.00072546
 * temperature * (humidity * humidity) - 0.000003582
 * (temperature * temperature) * (humidity * humidity));
}
```

Figure 4.11 The software of slave devices – part three (Personnel Archive, 2023)

Figure 4.12 shows the ‘setup’ function, which initializes the essential components of the IoT device, including serial communication for debugging, DHT and PIR sensors for data acquisition, and network connectivity via Wi-Fi and MQTT client configuration. The ‘loop’ function represents the main operational loop of the device, continuously checking and re-establishing the MQTT connection, managing incoming messages, and periodically monitoring the PIR sensor for motion detection. When motion is detected, the device retrieves temperature and humidity data from the DHT sensor, calculates the apparent temperature, and publishes both the PIR state and the apparent temperature to MQTT topics. To ensure optimal performance, there is a brief delay between iterations to regulate the frequency of message sending.

```
void setup() {
  Serial.begin(9600);
  delay(100);
  dht.begin();
  pir.begin();
  setup_wifi();
  client.setServer(mqtt_server, 8883);
  client.setCallback(callback);
}

void loop() {
  if (!client.connected()) {
    reconnect();
  }
  client.loop();
  unsigned long currentMillis = millis();
  // PIR Checkes
  bool pirVal = pir.read();
  if (pirVal && (currentMillis - lastPirDetectionTime > pirDetectionCooldown)) {
    lastPirDetectionTime = currentMillis;

    // Apparent temperature calculation and publishing.
    float dhtHumidity = dht.readHumidity();
    float dhtTempC = dht.readTempC();
    float apparentTemp = calculateApparentTemperature(dhtTempC, dhtHumidity);
    char appTempMsg[10];
    dtostrf(apparentTemp, 4, 2, appTempMsg);
    client.publish(APPARENT_TEMP_TOPIC, appTempMsg);

    // PIR Data Publishing
    char pirMsg[6];
    dtostrf(pirVal, 1, 0, pirMsg);
    client.publish(PIR_TOPIC, pirMsg);
  } delay(1000);}
```

Figure 4.12 The software of slave devices – part four (Personnel Archive, 2023)

4.3 Optimizing the Placement of Sensors

Optimizing the placement of sensors in a smart home involves intricate mathematical calculations, yet it is crucial to prioritize regions that are also optimized against the possibility of furniture rearrangement. Achieving the most effective sensor placement not only requires careful consideration of mathematical calculations but also demands a strategic choice of areas resilient to potential changes in furniture arrangements within the home. Furthermore, for accurate data collection in studies related to home sensor placement, it is imperative not only to consider the initial positioning of sensors but also to regularly calibrate them. The utilization of a methodology known as Building Information Modeling (BIM) facilitates these processes (Kassem et al., 2018). In this study, leveraging mathematical computations, particularly from the work on "Optimal Sensor Placement in Smart Home Using

Building Information Modeling: A Home Support Application" (Bachouch et al., 2021), sensor placements were meticulously determined. It is worth underscoring that beyond the initial deployment, consistent calibration, and consideration of potential changes in the home environment are pivotal for the sustained efficacy of sensor systems. Borissova et al. (2022) used sensors in their home modeling, as well as the same structure.

The study was conducted on a real-time model house. Insulation was applied to a house referred to as 2+1, constructed according to the current regulations in Türkiye. The term 2+1 denotes a house with two bedrooms, one living room, a kitchen, and at least one bathroom and toilet. Generally, houses have a corridor. Although the use of houses consisting of three bedrooms and one living room is more common in Türkiye, shown as Figure 4.13, the study used two bedroom and one living room house, particularly due to the construction of smaller houses in new constructions.

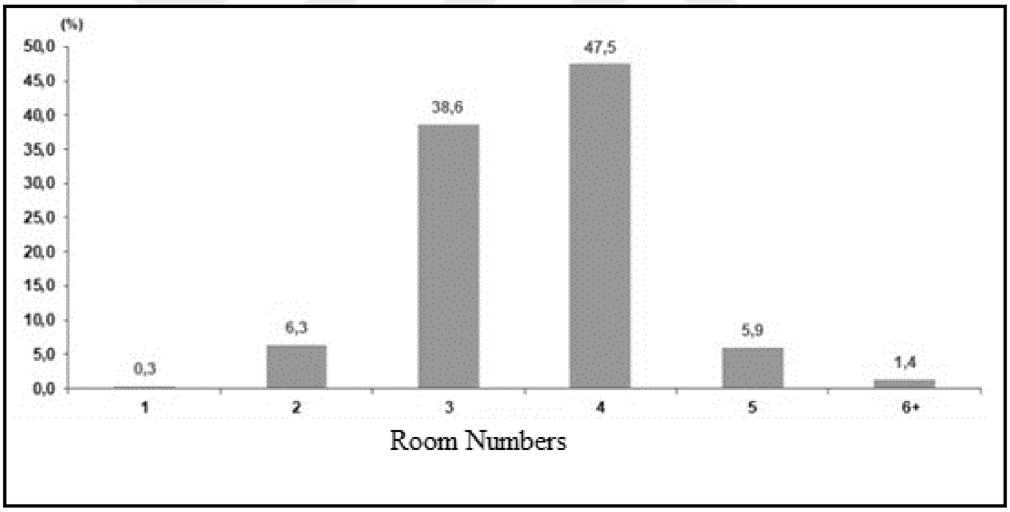


Figure 4.13 The rooms in the occupied residence in 2021 in Türkiye (TUIK, 2022)

The house where the application was implemented is in Bornova, Izmir, Türkiye. Details such as column projections and similar small elements have not been transferred onto the computer drawing (HomeByMe, 2023) in Figure 4.14 as they are deemed to have no impact.

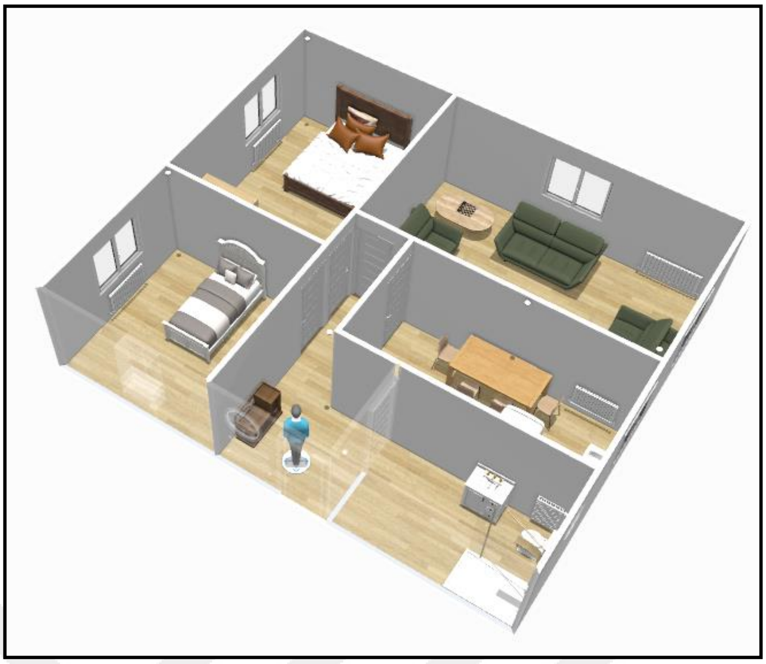


Figure 4.14 The view of the house with a transparent ceiling (Personnel Archive, 2023)

Six areas have been defined, each with wireless sensor modules placed on walls with the widest field of view, leaving a 10 cm distance from the ceiling. Figure 4.15 displays the names and placements of the modules, radiators, and solenoid valves. The square meter values for each room are shown in Figure 4.15.

Figure 4.15 The modules of the house with a transparent ceiling (Personnel Archive, 2023)

- M1: Bedroom1 Slave Module
- M2: Bedroom2 Slave Module
- M3: Living Room Salve Module
- M4: Kitchen Slave Module
- M5: Hallway Slave Module
- M6: Bathroom Slave Module
- R1: Bedroom1 Solenoid Valve
- R2: Bedroom2 Solenoid Valve
- R3: Livingroom Solenoid Valve
- R4: Kitchen Solenoid Valve
- R5: Hallway Solenoid Valve
- R6: Bathroom Solenoid Valve
- Master Unit: Master Control Module
- Combi Boiler: Gas-fired Heating Device

4.4 Selecting Combi Boiler and Weather Condition

The subject of the thesis study used the Bosch Condens 2000 W ZWB24-1AR 24KW model. This condensing combi boiler has achieved significant sales figures in the Turkish market as Bosch's first offering in this category. The study analyzed sales volume data for the combi boiler market in Türkiye from a confidential source in 2021. These data provide valuable insights into market trends and can inform industrial decisions.

The copper heat exchanger of the conventional boiler remains unchanged, but a condensation chamber has been added to the upper part. This chamber reduces the waste gas temperature from an average of 120℃ (before the advent of condensing boilers) to around 60℃. The lower waste gas temperature significantly improves efficiency by heating the water returning from the heating system and the cold water from the mains. Our research focuses on this boiler because of its proficiency in understanding the OpenTherm protocol (OpenTherm, 2003). To guarantee a thorough evaluation of all options, we selected days with identical daily temperatures. During the algorithm implementation, each hardware configuration underwent a 3-day testing period. Throughout this process, we used data from the location Türkiye, Izmir, Bornova on wunderground.com (Wunderground, 2023) and cross-referenced it with our external temperature sensor. When acquiring data, we took into account factors such as temperature, wind speed, and humidity. We used the daily average temperature as the baseline for temperature assessments.

Unfortunately, we were unable to replicate identical conditions in many tests, which made data recording infeasible. We determined that the most affordable dates for testing were December 5th, 6th, and 7th, 2023, as shown in Table 4.1 and Figure 4.16. The optimization tests were conducted in the following order: a combi boiler without a control unit, a combi boiler operating solely with an OpenTherm room controller, and finally, the MQTT-based and OpenTherm protocol-supported optimization, which is the focus of the research (OpenTherm, 2023).

Table 4.1 Weather condition between 5-7 December 2023 (Wunderground, 2023)

Time	**Temperature (℃)**			**Humidity (%)**		
December 2023	Max	Avg	Min	Max	Avg	Min
5	17.0	12.4	8.0	100	89.0	68.0
6	15.0	11.9	9.0	100	96.3	77.0
7	16.0	12.3	10.0	100	96.5	77.0

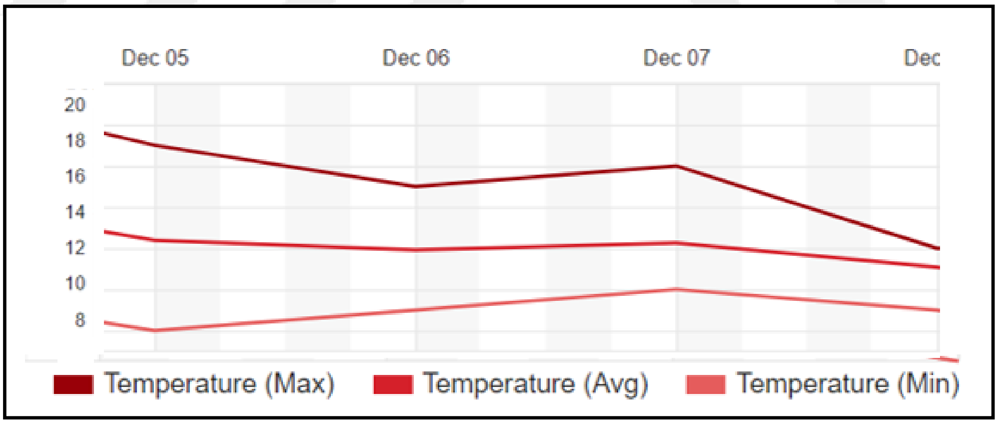


Figure 4.16 Average temperature between 5-7 December 2023 (Wunderground, 2023)

CHAPTER FIVE
RESULTS AND CONCLUSIONS

A sophisticated home heating system is being imagined, which employs related devices. The system is controlled by a Master NodeMCU, with Slave NodeMCU modules placed strategically across rooms. The primary objective is to create an intelligent and energy-efficient heating infrastructure by assimilating data from an array of sensors, enhancing both efficiency and responsiveness.

The system consists of a Master NodeMCU that serves as the central hub, communicating with the central heating apparatus through the OpenTherm protocol. Additionally, NodeMCU modules are placed in various rooms to function as sensory appendages. These modules are equipped with sensors to monitor temperature, humidity, and motion levels. Their purpose is to collect environmental data and control heating valves connected to radiators.

The components work together seamlessly through the MQTT protocol. Each NodeMCU is assigned a unique MQTT topic to prevent data streams from merging and to maintain information integrity. The NodeMCU collects data from various sensors, interprets temperature, humidity, and motion nuances, and transmits this information to the Master NodeMCU in JSON format via MQTT. Additionally, the relays function as sentinels, localized to heating valves and operating in tandem with directives received from the Master NodeMCU.

The Master NodeMCU serves as the conductor of this system, facilitating communication between the OpenTherm protocol and the intricacies of home heating. It enables real-time coordination through Wi-Fi connectivity and precise communication with each NodeMCU via MQTT, embodying the essence of intelligent heating. The user interface features an LCD keypad, an extension of the Master NodeMCU, which serves as the portal for human interaction. Users can easily set personalized target temperatures for each room and view real-time data. The system's operational logic is sophisticated and aims for efficiency, providing customized heating by adjusting individual room temperatures to accommodate motion and external temperatures. Essentially, it is a personalized climate curator for the modern home.

5.1 First Condition Test

On December 5, 2023, the test for the 'Combi Boiler Without Thermostat' was conducted. The boiler was configured to operate according to its own algorithm by bridging the terminals of the thermostat. The flow temperature on the boiler was set to 50°C. The average outdoor temperature during the first day was 12.3°C, while the average home temperature remained at 21.4°C. At the end of the 24-hour period, the gas meter showed a natural gas consumption of 5.621m3. It consumed 0.821 kW/h electrical energy.

5.2 Second Condition Test

The test for the 'Combi Boiler with OpenTherm Compatible Thermostat CR50' was conducted on December 6, 2023, in Figure 5.1. The flow temperature of the boiler was set to 50°C, but OpenTherm can adjust the temperature as needed. The average outdoor temperature on the second day was 11.9°C, while the average home temperature remained at 21.2°C. At the end of the 24-hour period, the gas meter showed a natural gas consumption of 5.119m3. It consumed 0.772 kW/h electrical energy.

Figure 5.1 Operating with Bosch CR50 OpenTherm thermostat (Personnel Archive, 2023)

5.3 Third Condition Test

The test of the 'Combi Boiler with MQTT based OpenTherm Compatible Optimization System' was conducted on December 7, 2023. The boiler temperature was set to 50°C, but our optimization system controlled each point. Table 5.1 shows PIR activities. The average outdoor temperature on the third day was 12.3°C, and the average home temperature was 21.3°C. It consumed 0.689 kW/h electrical energy.

Table 5.1 The detection time of PIR (Personnel Archive, 2023)

Time	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
06:00:00	*	*	*	*	*	*
08:00:00	*	*	*	*	*	*
08:00:04	*	*	*	**ON**	*	*
08:00:42	*	*	*	*	**ON**	*
08:01:02	*	*	*	*	*	**ON**
08:03:04	*	*	*	*	*	**ON**
08:06:22	*	*	*	*	**ON**	*
08:06:27	*	**ON**	*	*	*	*
08:08:31	*	**ON**	*	*	*	*
08:10:13	*	*	*	*	**ON**	*
08:10:19	*	*	**ON**	*	*	*
08:12:32	*	*	**ON**	*	*	*
08:16:41	*	*	**ON**	*	*	*
08:18:53	*	*	**ON**	*	*	*
08:20:58	*	*	**ON**	*	*	*
08:21:05	*	*	*	*	**ON**	*
08:21:08	*	*	*	**ON**	*	*
08:23:12	*	*	*	*	**ON**	*
08:23:15	*	*	*	*	*	**ON**
08:25:22	*	*	*	*	*	**ON**
08:26:08	*	*	*	*	**ON**	*
12:13:06	*	*	*	*	**ON**	*
12:13:12	**ON**	*	*	*	*	*
12:15:21	**ON**	*	*	*	*	*
12:15:36	*	*	*	*	**ON**	*
12:15:39	*	*	**ON**	*	*	*
12:17:57	*	*	**ON**	*	*	*
12:20:09	*	*	**ON**	*	*	*
12:22:17	*	*	**ON**	*	*	*
12:24:21	*	*	**ON**	*	*	*
12:25:38	*	*	*	*	**ON**	*
12:25:40	*	*	*	*	*	**ON**
12:28:43	*	*	*	*	*	**ON**
12:25:38	*	*	*	*	**ON**	*
19:21:38	*	*	*	*	**ON**	*
19:21:55	*	*	*	*	*	**ON**
19:23:59	*	*	*	*	*	**ON**
19:26:02	*	*	*	*	*	**ON**
19:27:44	*	*	*	*	**ON**	*
19:27:50	**ON**	*	*	*	*	*
19:28:11	*	**ON**	*	*	*	*
19:28:31	*	*	**ON**	*	*	*
19:31:14	*	*	**ON**	*	*	*
19:33:29	*	*	**ON**	*	*	*
19:36:56	*	*	**ON**	*	*	*
19:38:59	*	*	*	*	**ON**	*
19:39:02	*	*	*	**ON**	*	*
19:41:23	*	*	*	**ON**	*	*
19:43:34	*	*	*	**ON**	*	*
19:45:41	*	*	*	**ON**	*	*
19:46:03	*	*	*	*	**ON**	*
19:46:06	*	*	**ON**	*	*	*
19:53:39	*	*	**ON**	*	*	*
19:55:40	*	*	**ON**	*	*	*
19:58:29	*	*	**ON**	*	*	*
19:59:32	*	*	*	*	**ON**	*
19:59:36	*	*	*	**ON**	*	*
20:00:00	*	*	*	*	*	*

At the end of the 24-hour period, the gas meter showed a natural gas consumption of 4.966m3. Figure 5.2 shows the pre-test condition, measured at 8415.547 m3. The increase was 4.966 m3. After the final test, the volume increased to 8420.513 m3, as seen in Figure 5.3. Electrical consumption is measured by power meter in Figure 5.4.

Figure 5.2 Natural gas cubic metering before third condition test (Personnel Archive, 2023)

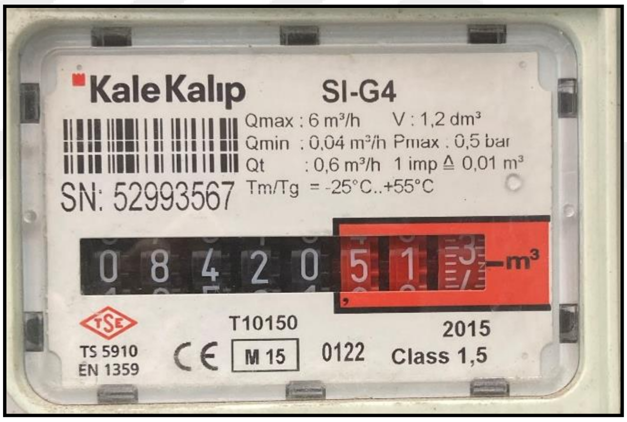


Figure 5.3 Natural gas cubic metering after third condition test (Personnel Archive, 2023)

Figure 5.4 Electrical consumption for third condition test (Personnel Archive, 2023)

5.4 Results

Tests were conducted for three days under suitable conditions to perform testing. Table 5.2 shows that energy consumption increased when room control was not utilized. However, with modulating room controllers equipped with OpenTherm protocol, consumption was slightly reduced. During the final day of testing, the system operated using MQTT and demonstrated a significant improvement in energy efficiency. Specifically, electricity consumption was reduced by 16.12% and 10.75% compared to the scenario without any room control and CR50. Additionally, gas consumption was 11.65% more efficient compared to the scenario without any room control and 4.84% more efficient compared to modulating room controllers with knowledge of the OpenTherm protocol. Result table consumption gives only combi boiler consumption.

Table 5.2 Result table (Personnel Archive, 2023)

	Combi Boiler Without Thermostat	Combi Boiler with OpenTherm Compatible Thermostat	Combi Boiler with MQTT based OpenTherm Compatible Optimization System
Date	5 December 2023	6 December 2023	7 December 2023
Evaluate Hours	24 Hours	24 Hours	24 Hours
Electrical Power Consumption kW/h	0.821	0.772	0.683
Natural Gas Consumption m^3/h	5.621	5.219	4.966
Average Day Temperature	12.4	11.9	12.3
Average Home Temperature	21.3	21.2	21.3
Cost of System	-	$123	$130.22

Insulation significantly impacts the efficiency of devices. Therefore, it is important to consider insulation when evaluating results. The tests in this study were conducted under the same insulation and weather conditions to ensure accurate comparisons.

Additionally, the study found that lower flow temperatures in combi boilers result in better condensation, which in turn increases efficiency. During our tests, we found that the device's maximum outlet temperature did not exceed 50°C. To reduce energy consumption, we recommend eliminating heating demand in unused rooms and setting different target temperatures for each room.

When examining seasonal efficiency, it was found to decrease to 16℃ or below between November 1 and March 31 in the tested region. Figure 5.5 illustrates that daily values are multiplied by 150 to equal five months. Options without a thermostat may have a difference of 98.25 cubic meters for the entire season. Based on the 2024 data from Izmir Gas, the price per cubic meter is $0.22. Additionally, the user is charged $21.61 seasonally. Electrical consumption is calculated as 123.15kW/h, 115.8kW/h, and 102.35kW/h.

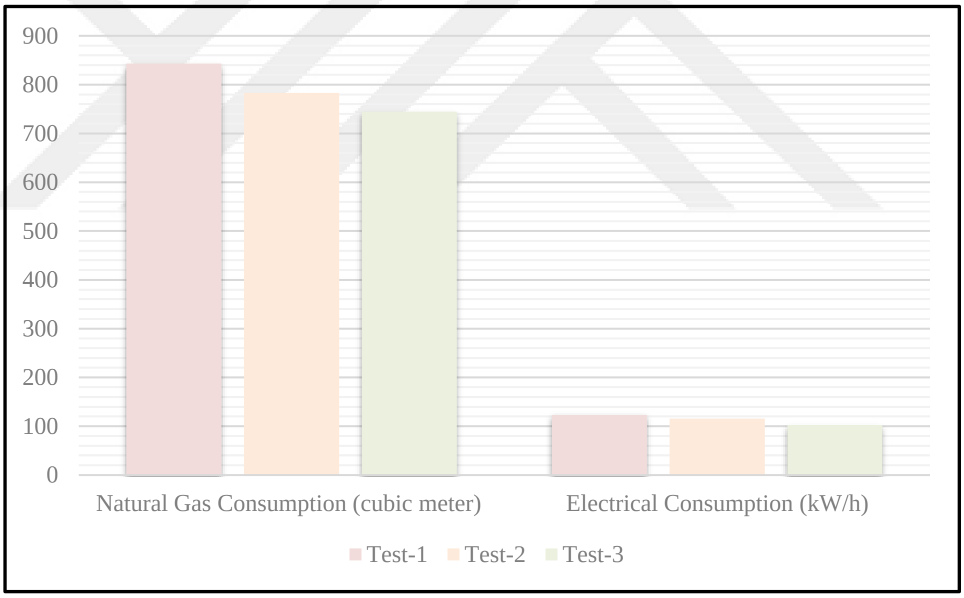


Figure 5.5 The seasonal consumption values over a period of 150 days. (Personnel Archive, 2023)

Currently, the Bosch CR50 room controller is priced at $123, while the CR100 offers additional program capabilities and costs $141 (Hepsiburada & Amazon, 2024). The system cost of the thesis is $130.22, as indicated in Table 5.3. It is normal to have a price difference due to the comfort provided in each room, so a cost difference of 5.6% is acceptable.

Table 5.3 Cost calculation of thesis study (Personnel Archive, 2024)

Material	**Pieces**	**Piece Cost**	**Cost**
NodeMCU	7	$4	$28
OpenTherm Adaptor	1	$1.45	$1.45
DHT22 Sensor	7	$2.11	$14.77
PIR Sensor	6	$1.90	$11.4
Solenoid Valve	6	$6.5	$39
12V External Power Supply	7	$2.3	$16.1
Output Module	7	$1.2	$8.4
Relays	6	$1.1	$6.6
Cables and Sockets	1	$4.5	$4.5
		Total Cost	$130.22

The study's results suggest that devices such as electric boilers, heat pumps, and air conditioners can achieve similar efficiencies to those obtained in gas regions. Heat pumps are particularly popular in Europe, while air conditioners have been widely used in homes for years.

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